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Savord

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(54) **ULTRASOUND TRANSMIT WAVEFORMS HAVING LOW HARMONIC CONTENT**

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(52) **U.S. Cl.** **600/447**
(58) **Field of Search** 680/447; 600/443, 600/437, 448, 458, 447

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(57) **ABSTRACT**

Methods and apparatus for transmitting ultrasound energy having low harmonic content and for detecting harmonic reflections of the ultrasound energy are disclosed. According to the invention, the capacitance of an ultrasound transducer element, as well as any interconnection capacitance associated with one or more signal conductors attached to the transducer element, is utilized as part of a filter which conditions one or more electronic drive signals to provide an ultrasound transmit waveform having low harmonic content. Such a low harmonic content ultrasound transmit waveform may be used to expose a region of interest in a patient which reflects harmonics of the transmit waveform. Receive circuitry detects the harmonic reflections and generates an ultrasound image having improved contrast and reduced distortion.
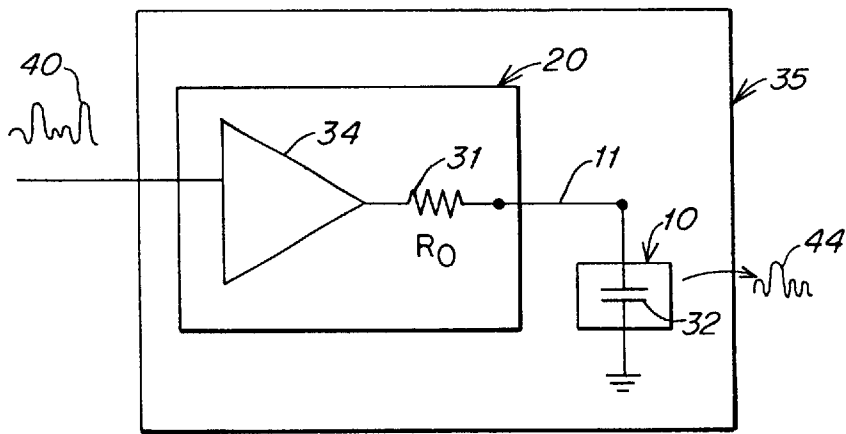
24 Claims, 14 Drawing Sheets
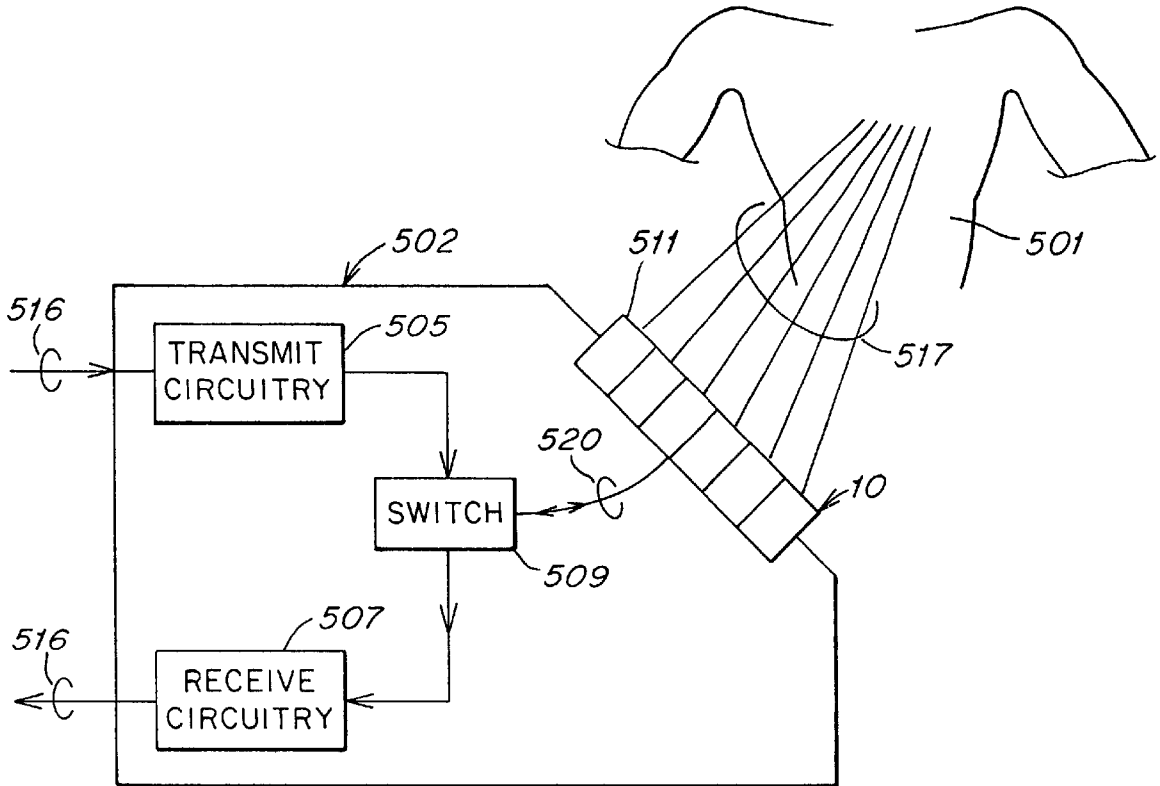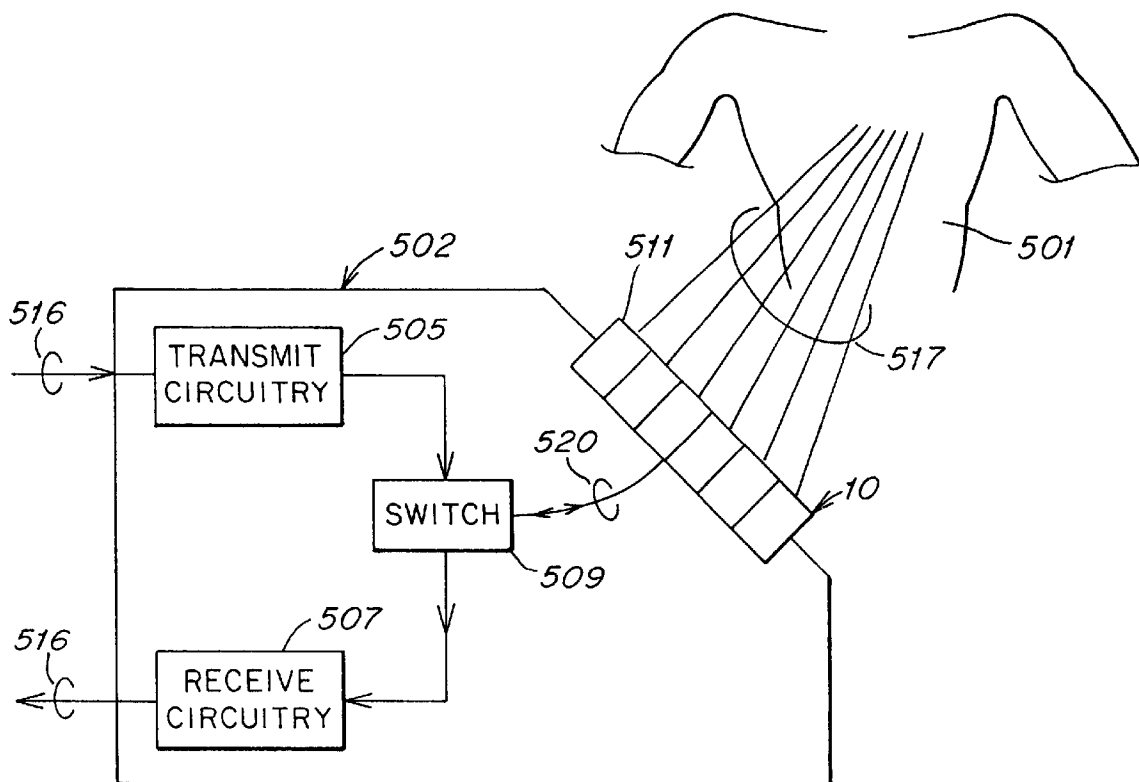
FIG. 1

FIG. 2A
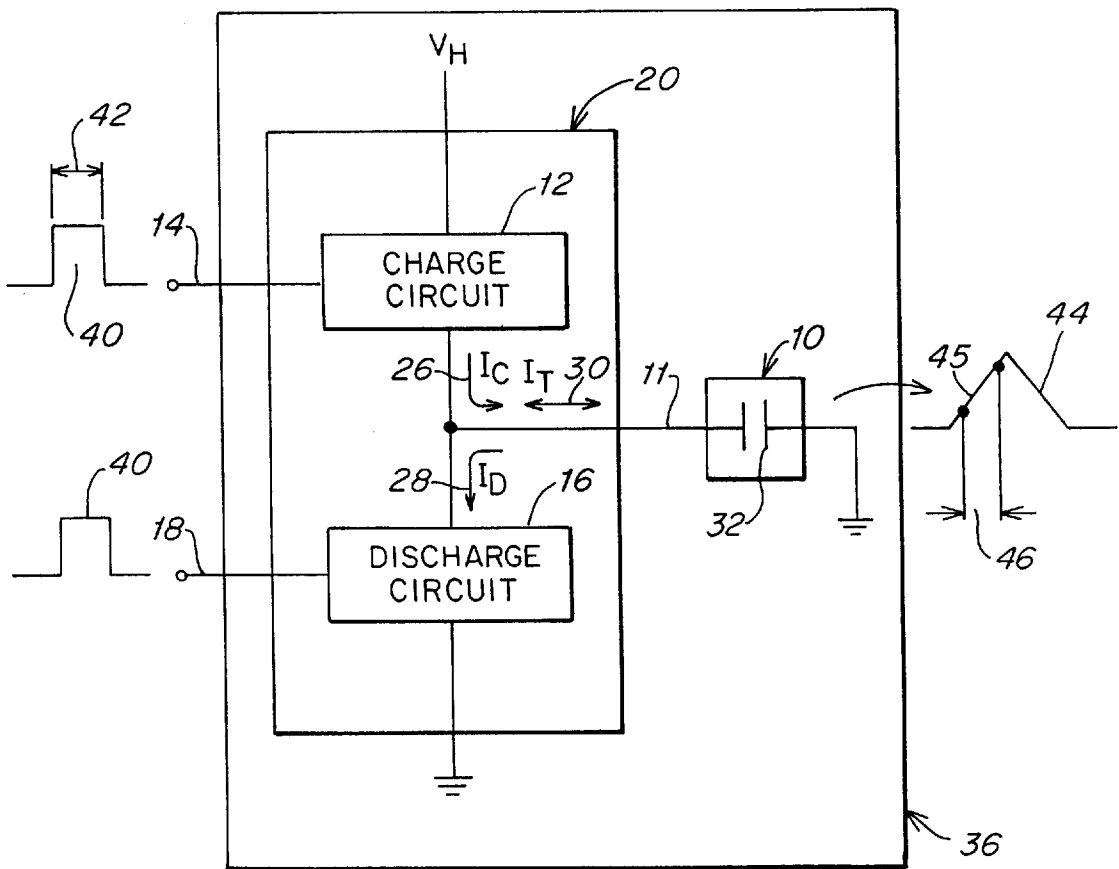
FIG. 2B

FIG. 3A

FIG. 3B

FIG. 4A

FIG. 4B

FIG. 5A

FIG. 5B

FIG. 6A

FIG. 6B

V

14

12
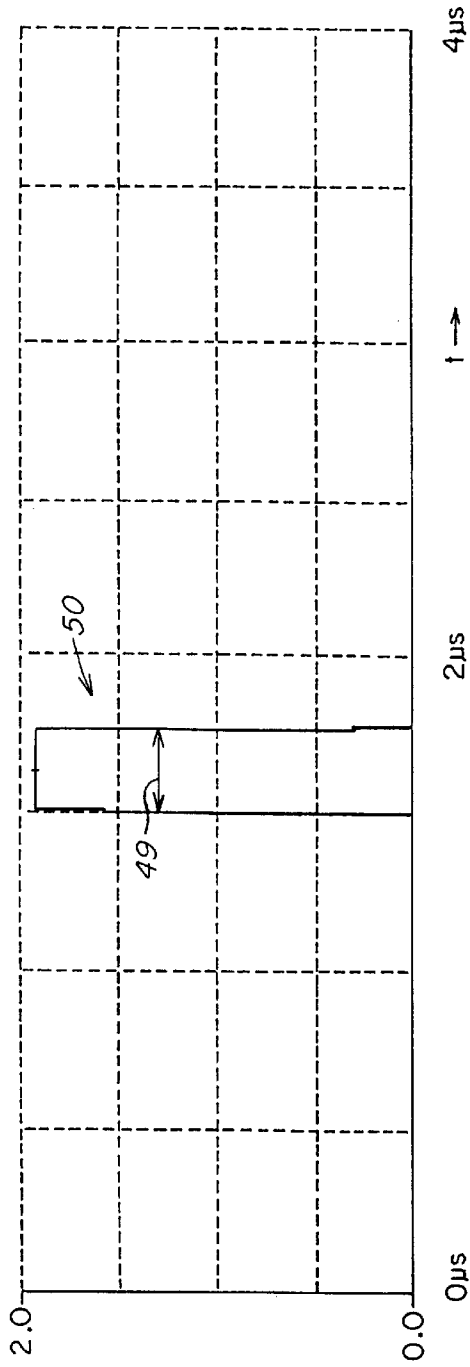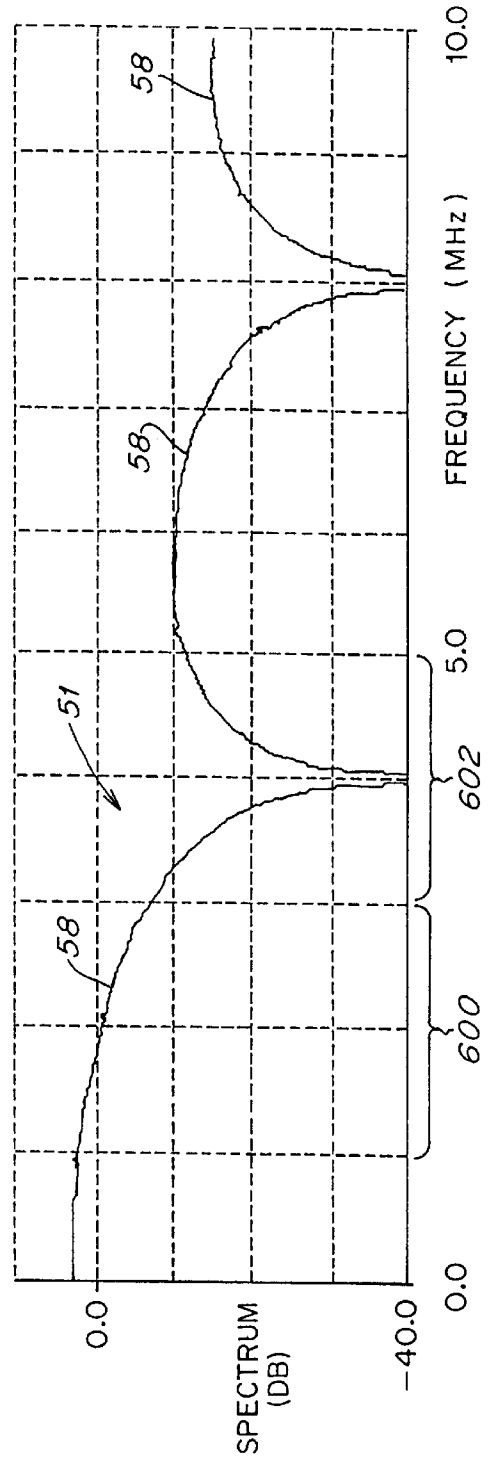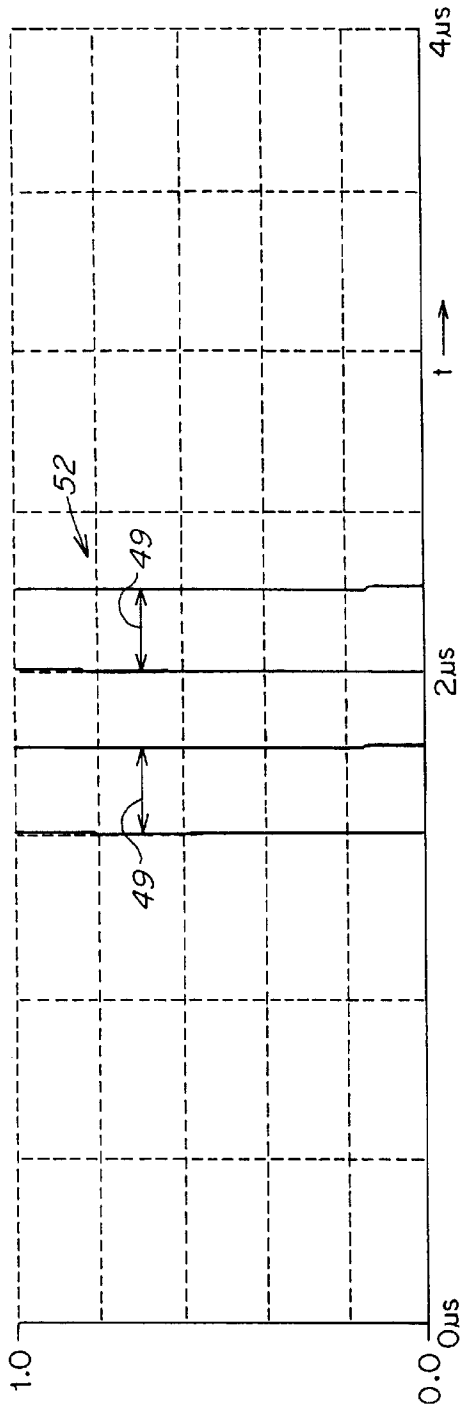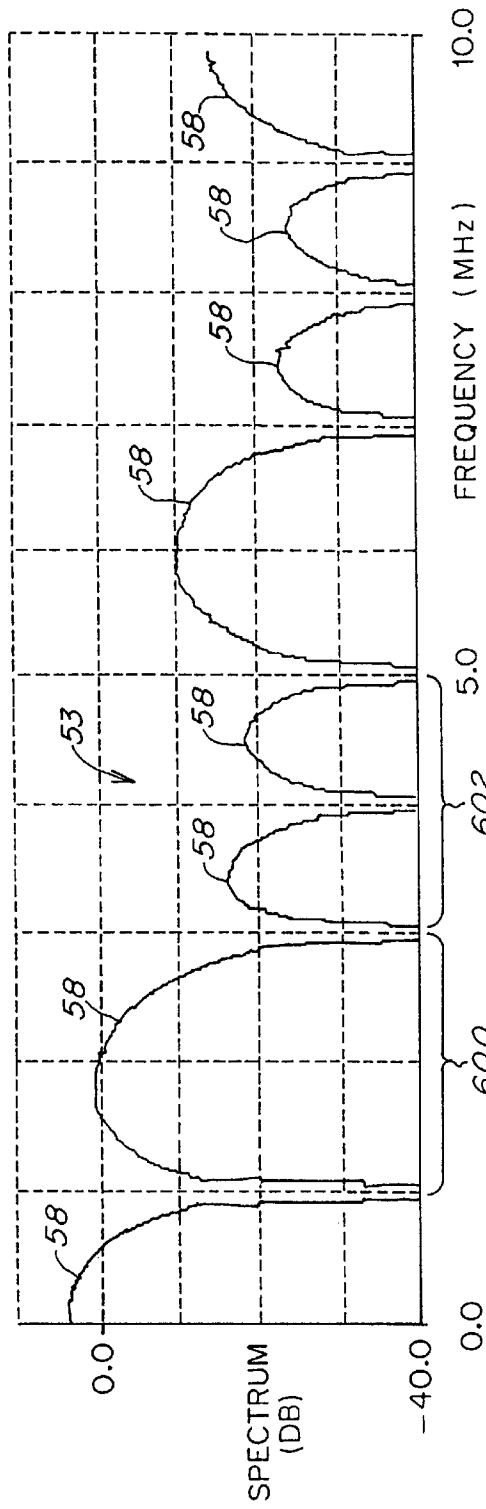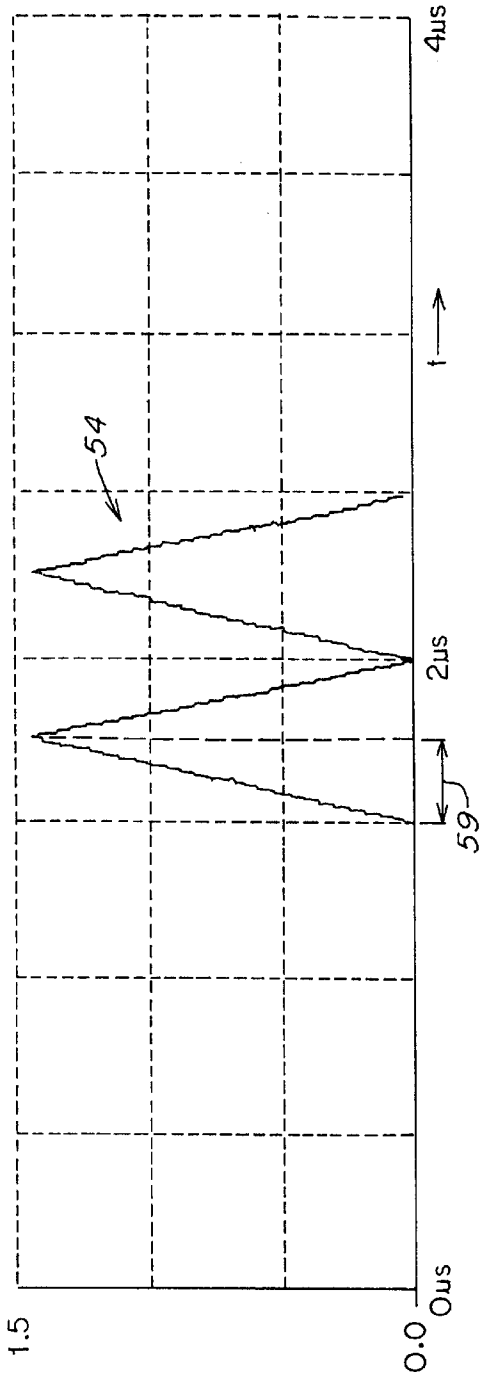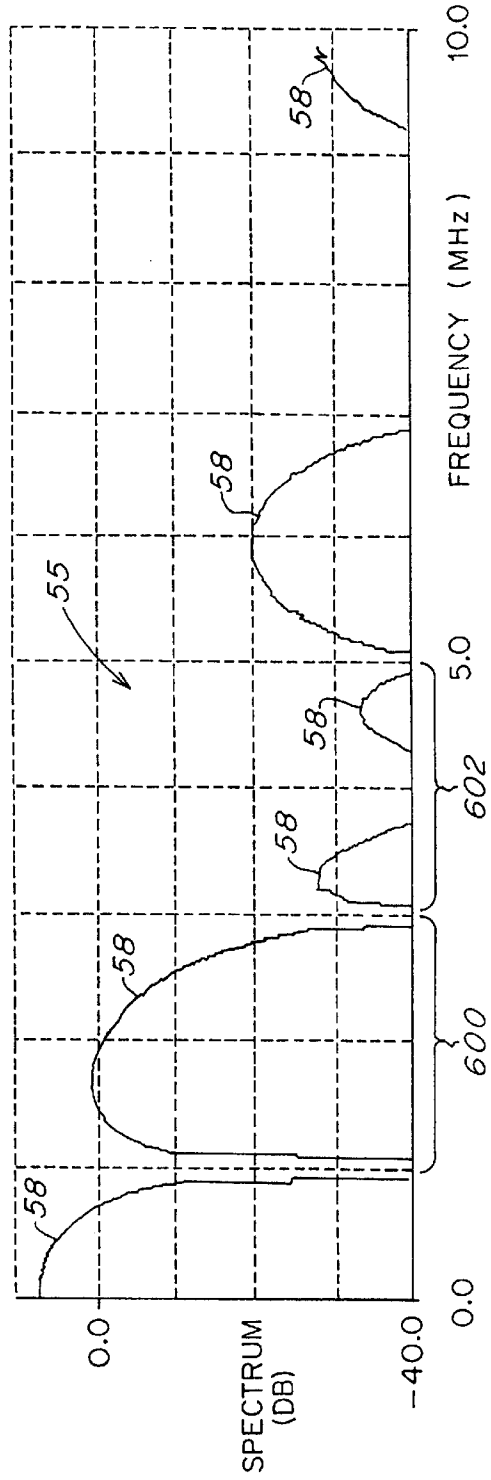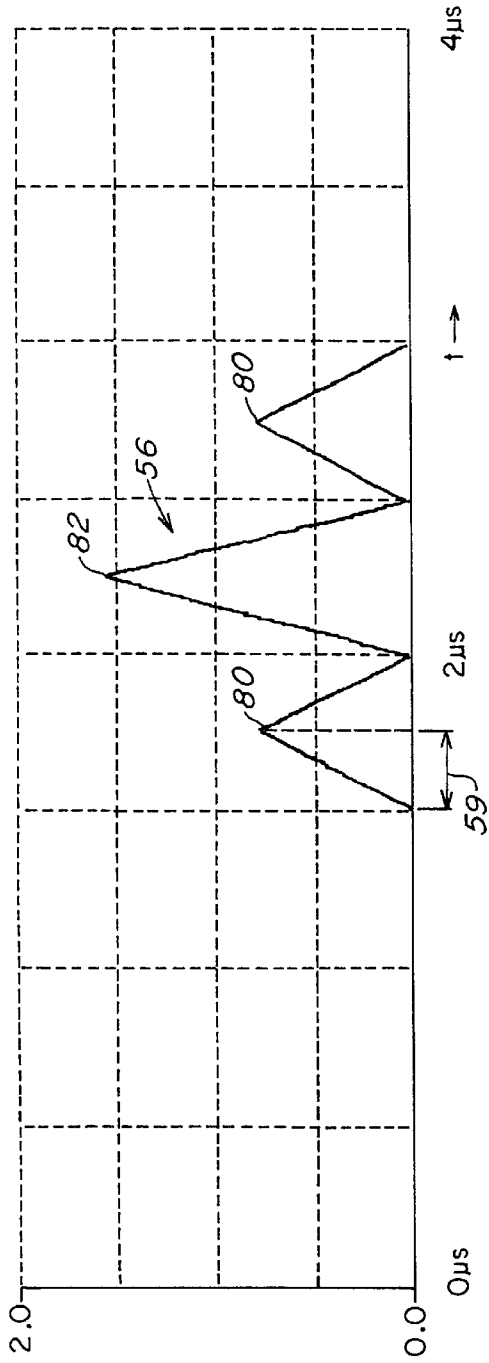
22

I_C

26

FIG. 7

V_H
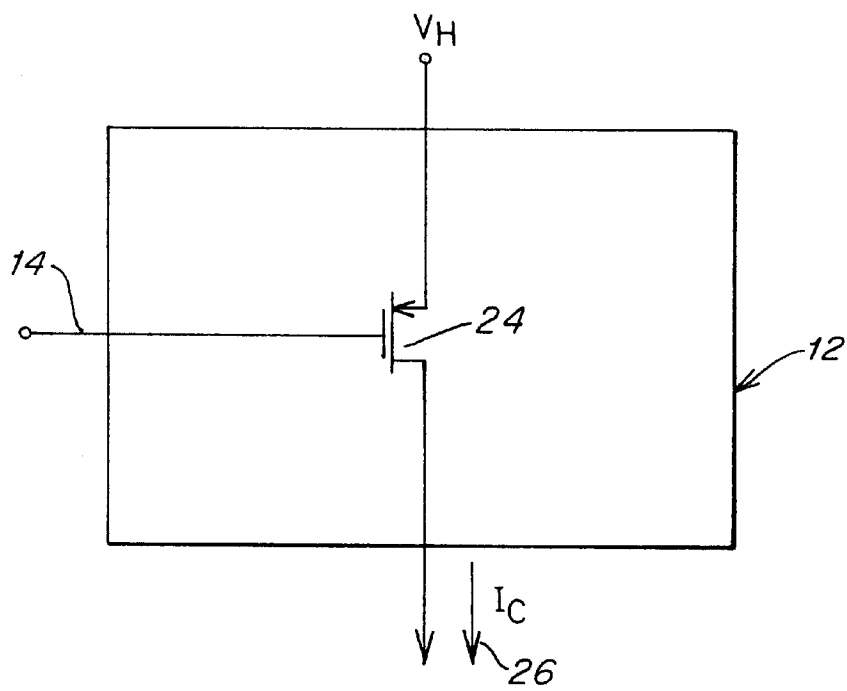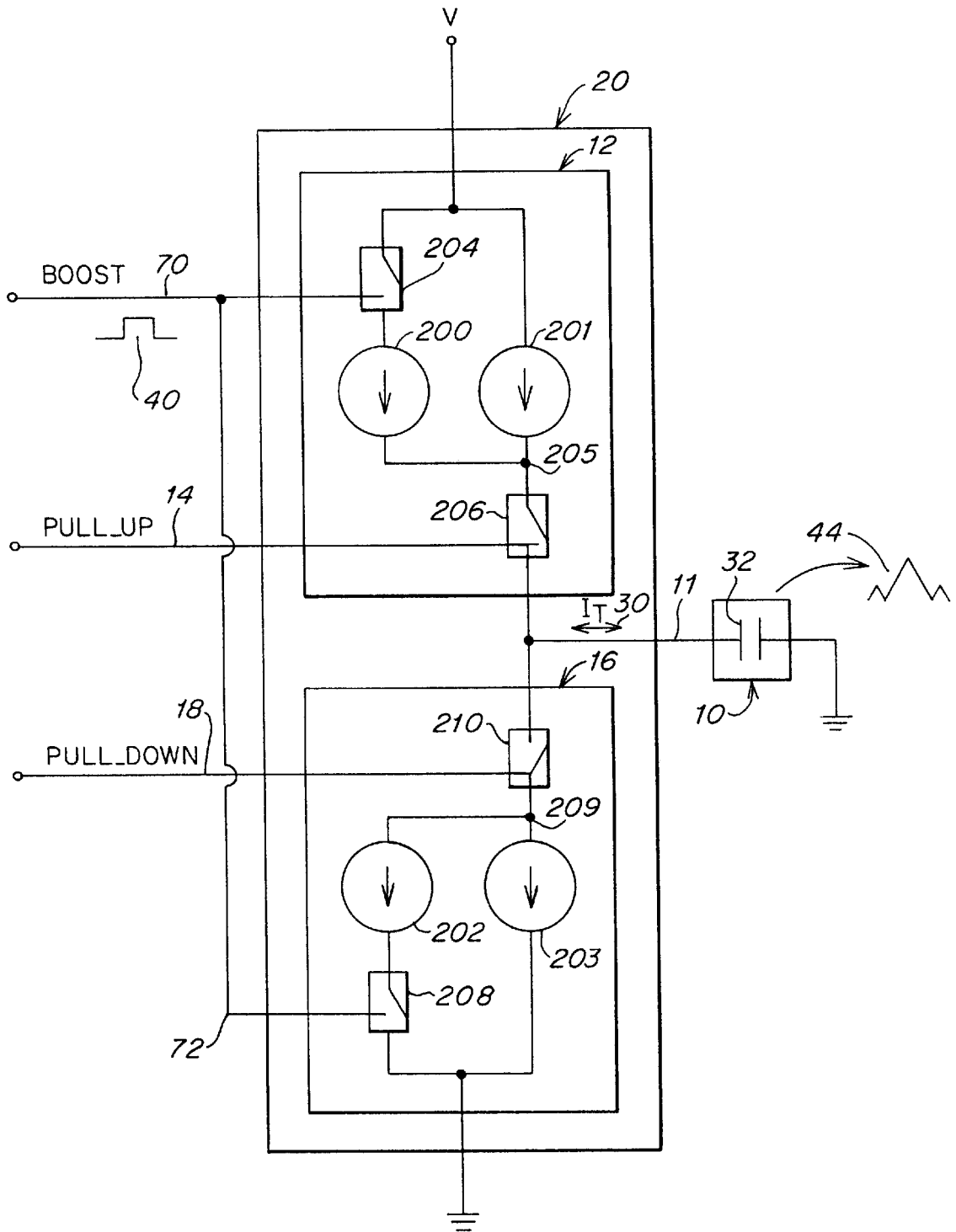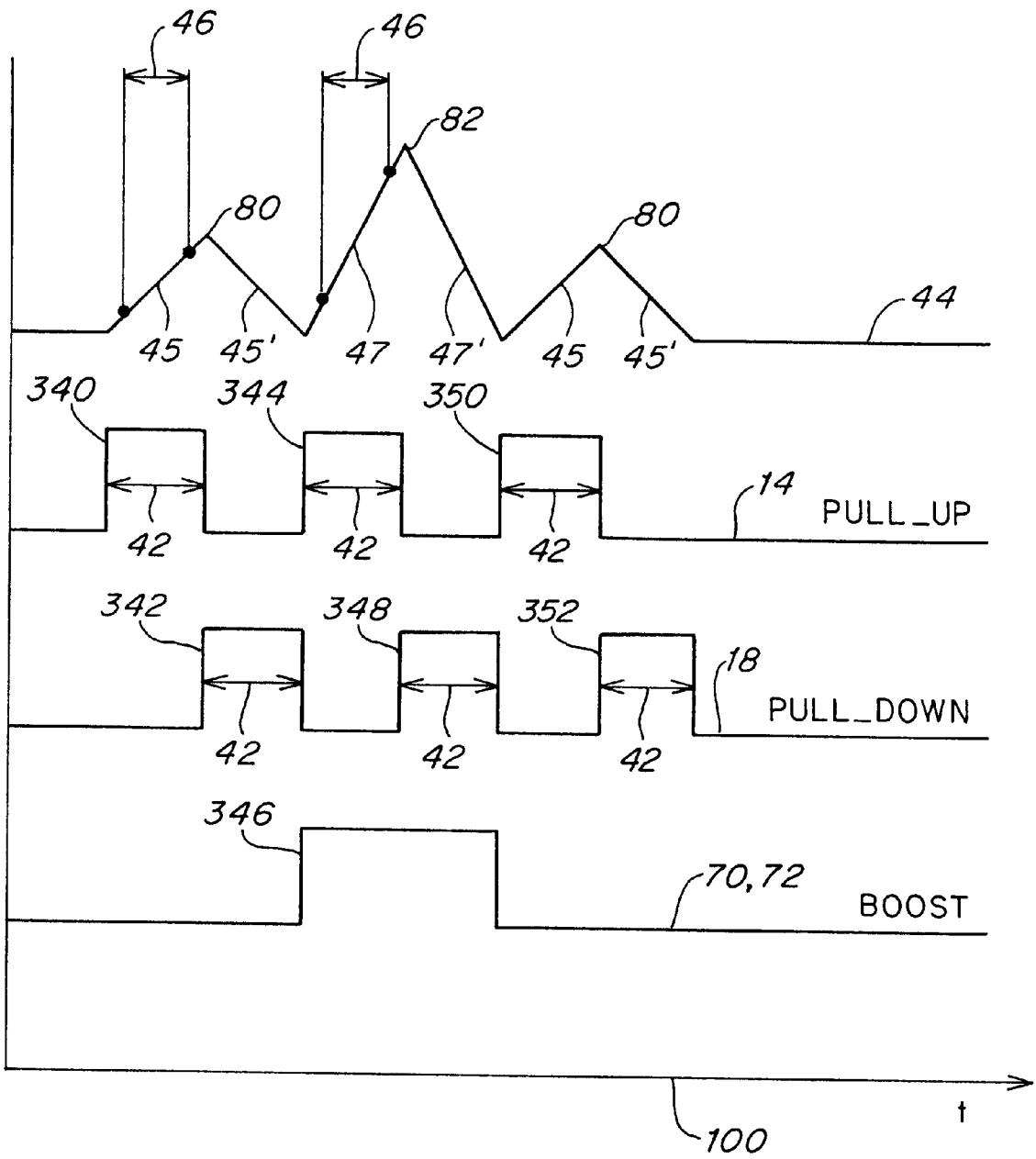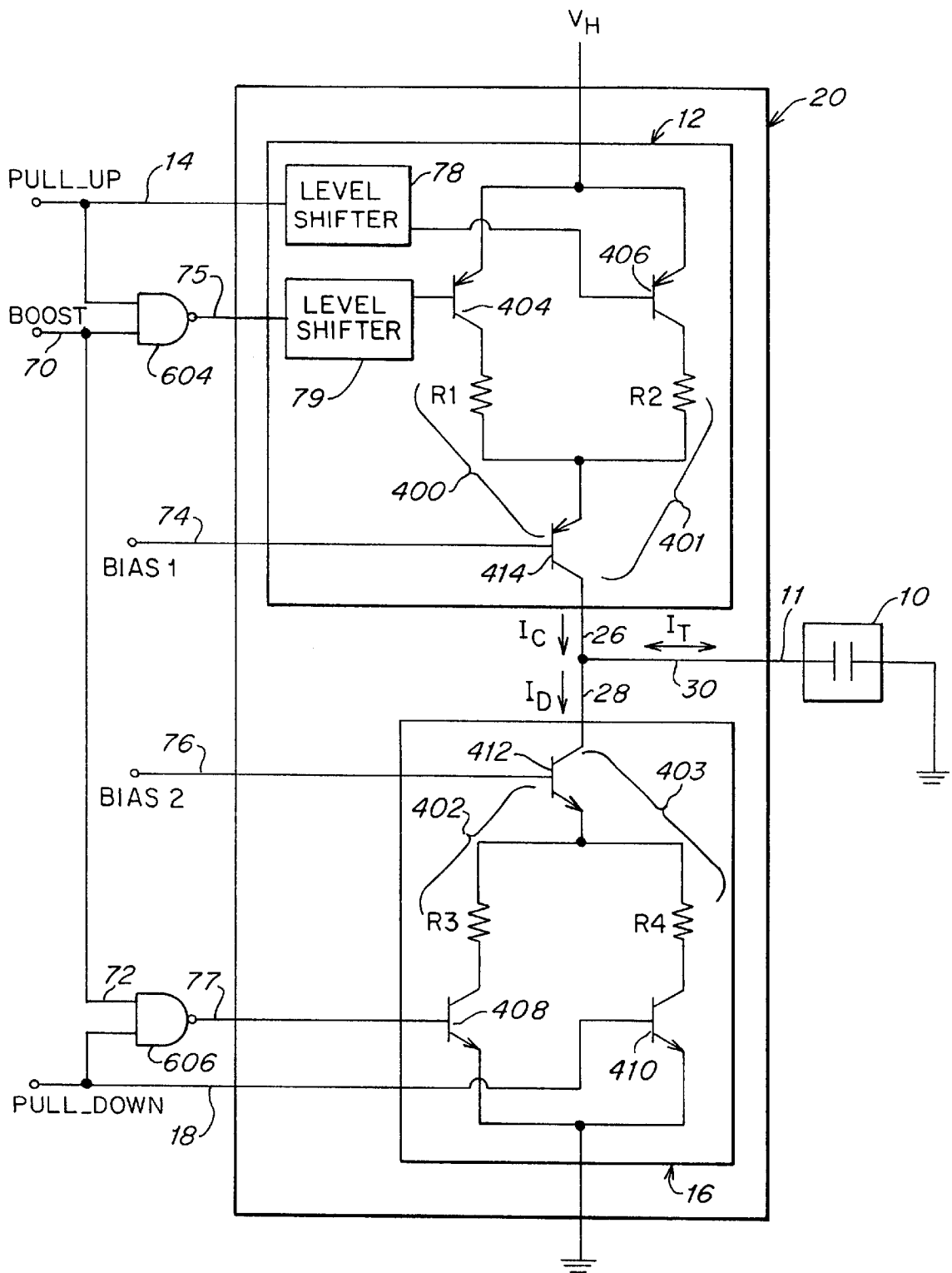
14

24

12

I_C

26
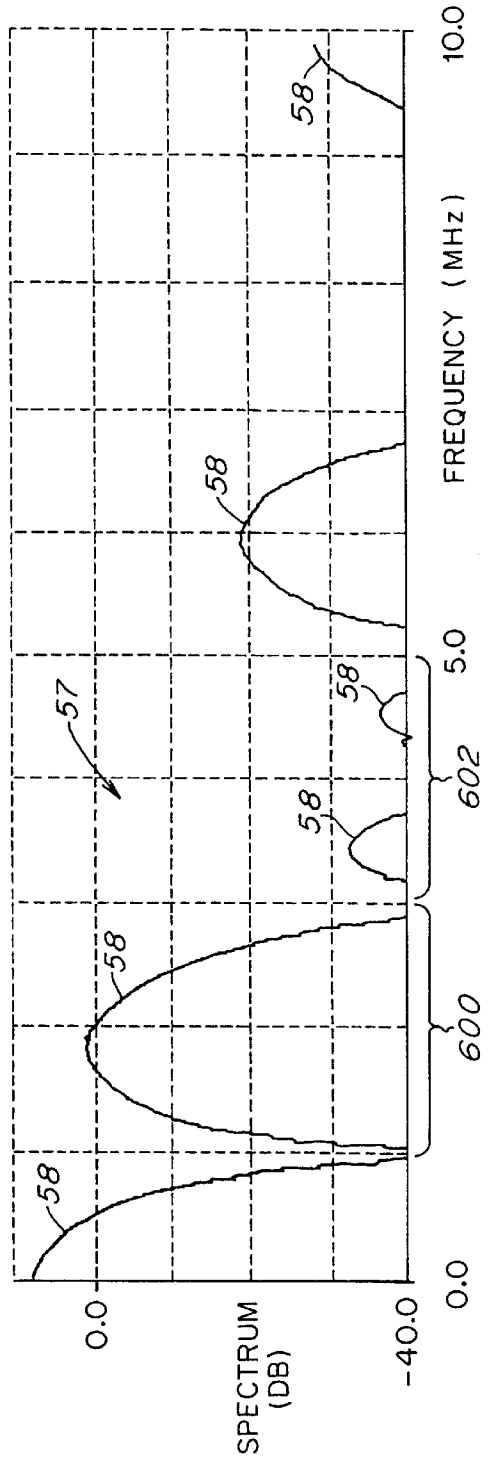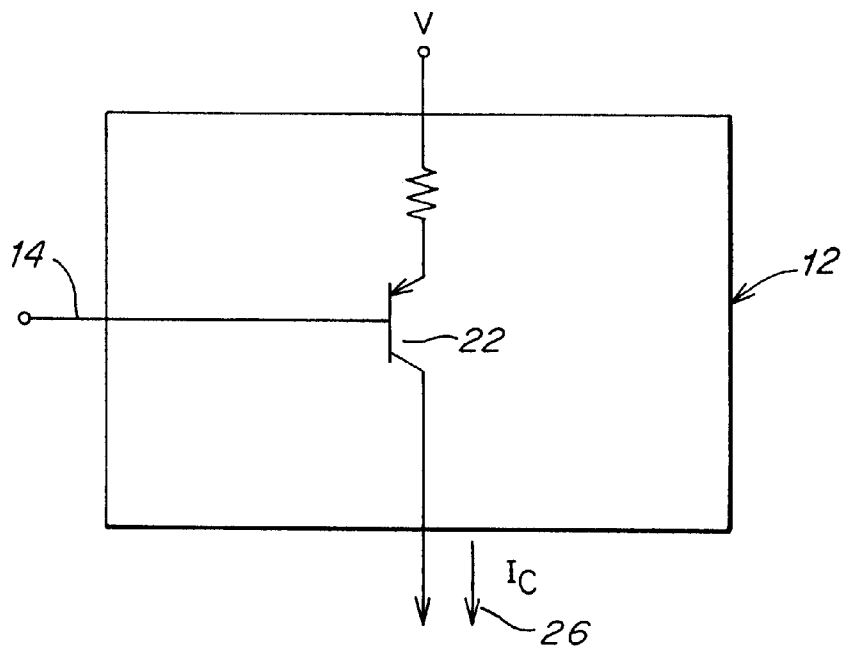
FIG. 8
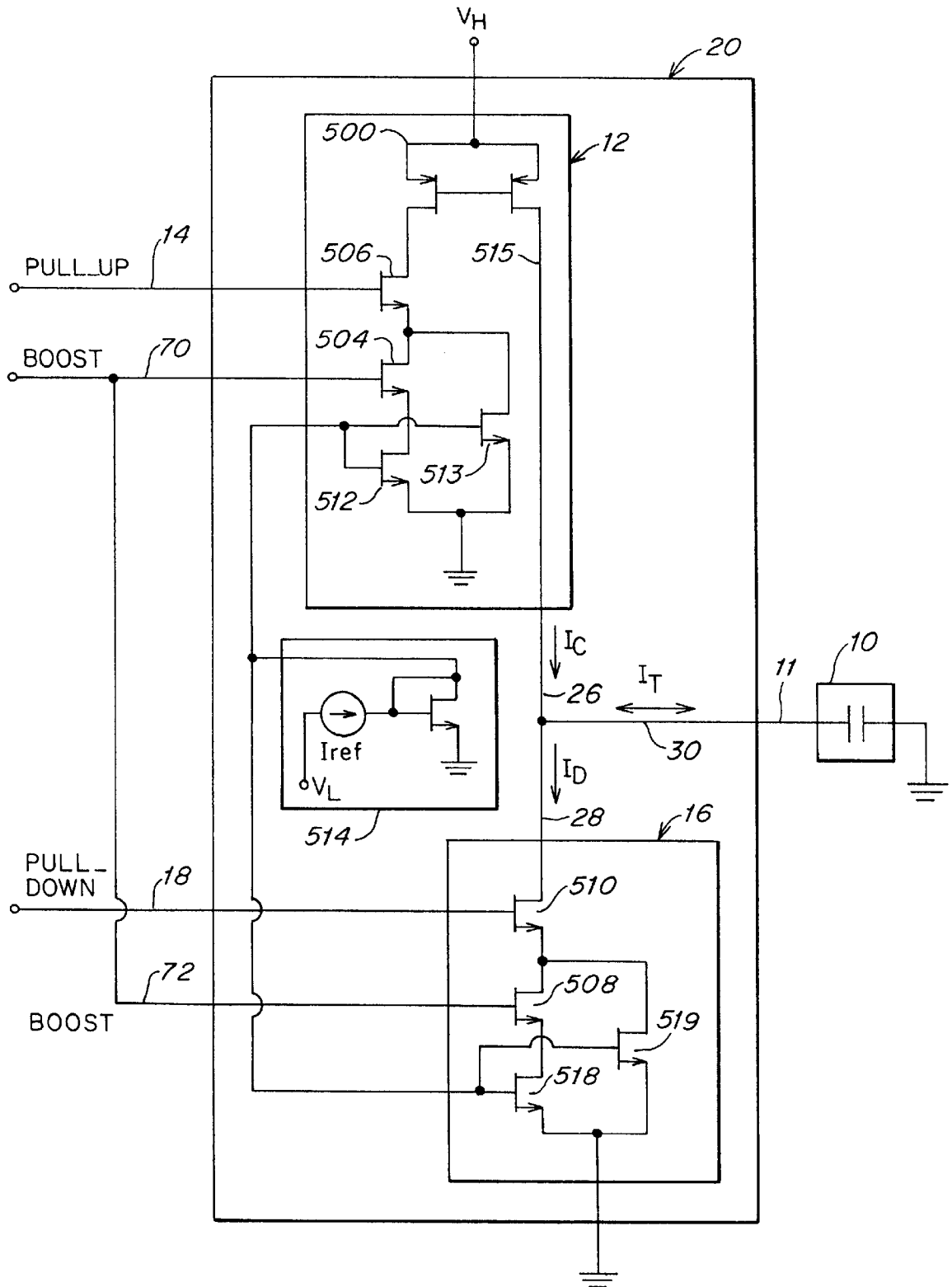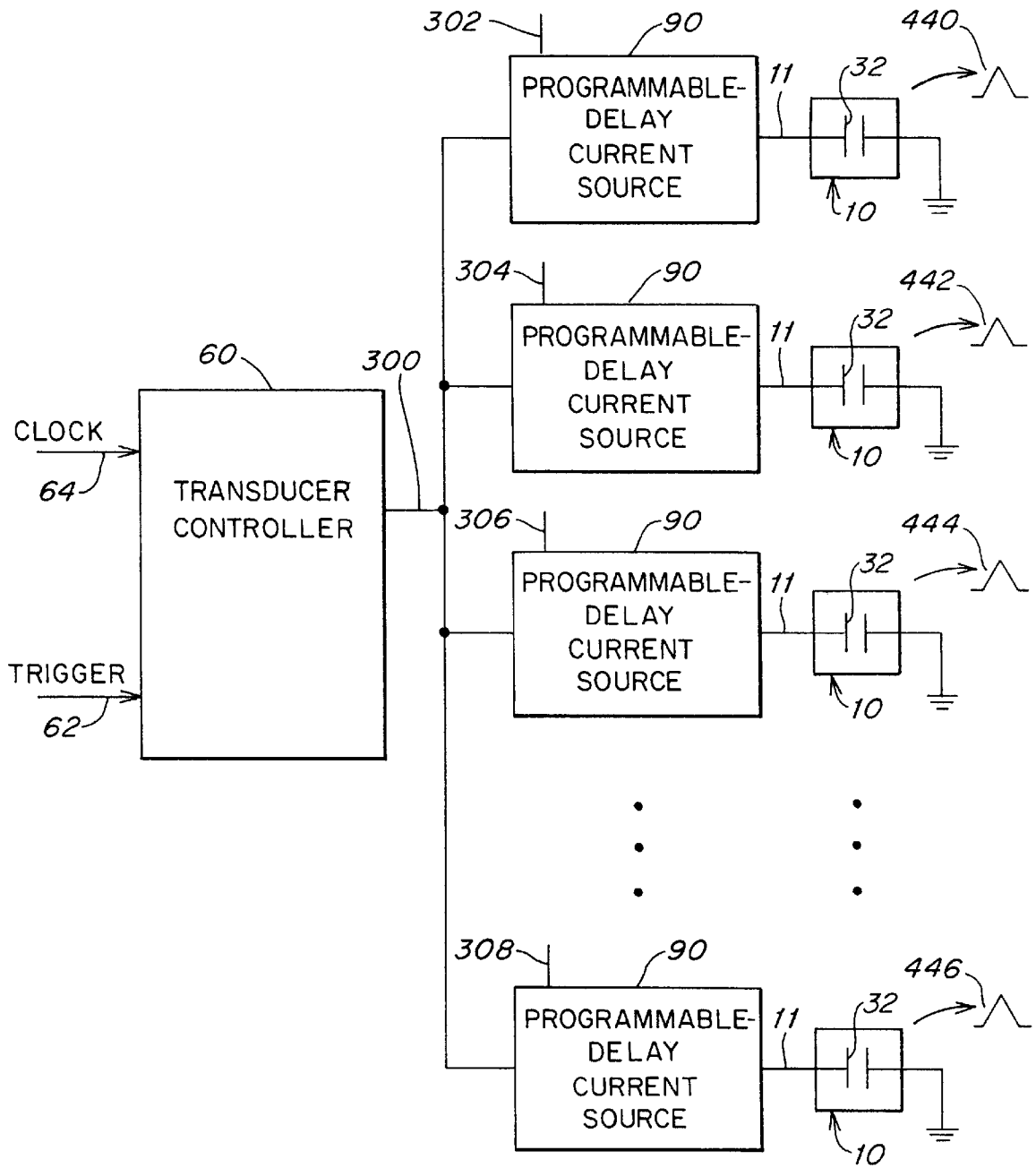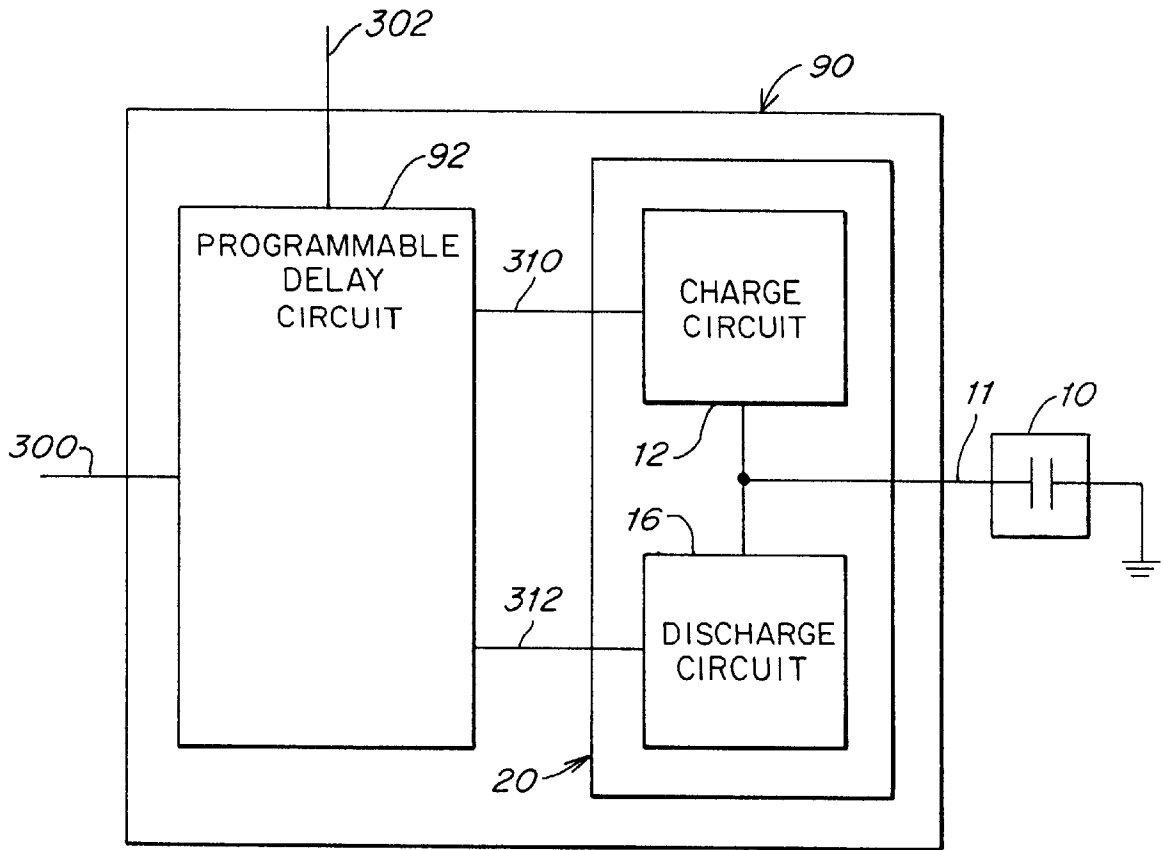
FIG. 9

FIG. 10

FIG. 11
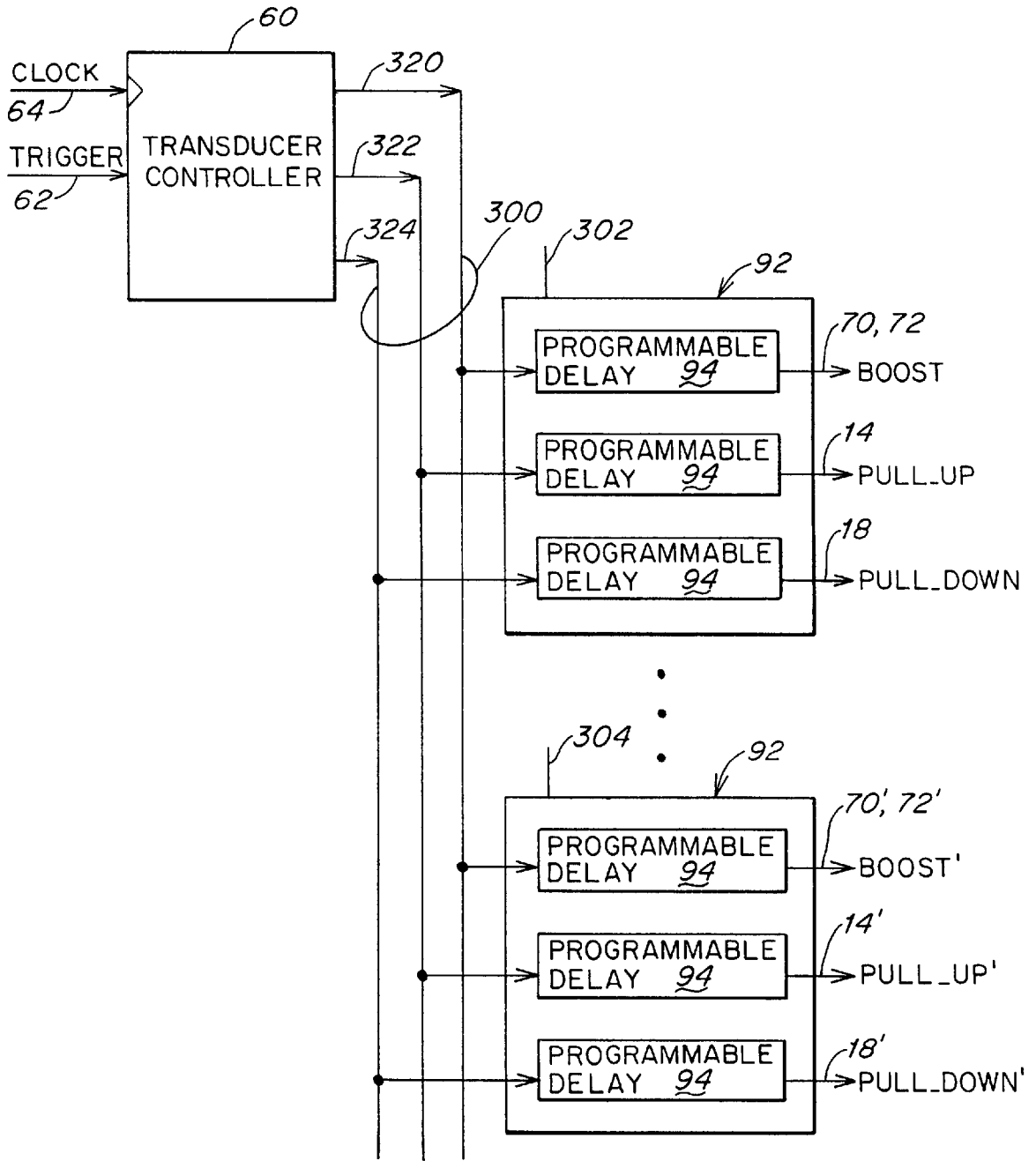
FIG. 12

FIG. 13

FIG. 14

FIG. 15

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ULTRASOUND TRANSMIT WAVEFORMS HAVING LOW HARMONIC CONTENT

FIELD OF THE INVENTION

This invention relates to harmonic ultrasound imaging for medical applications and, more particularly, to methods and apparatus for transmitting ultrasound energy having waveforms with low harmonic content and for detecting harmonic reflections of the ultrasound energy.

BACKGROUND OF THE INVENTION

Ultrasound imaging systems for medical applications typically employ an array of individual ultrasound transducer elements which transmit and receive ultrasound energy. The transducer array transmits ultrasound energy into a region of interest in a patient, and receives reflected ultrasound energy, or echos, from various structures and organs within the patient's body. The imaging system then processes electronic signals generated by the elements of the transducer array, based on the received ultrasound energy, to form an image of the region of interest.

Some ultrasound imaging applications make use of harmonic reflections from a region of interest for which an image may be desired. Harmonic reflections may result from a non-linear medium that is exposed to ultrasound energy at some fundamental transmit frequency. One example of such a non-linear medium includes water, which is present throughout body tissues and has different expansion and compression properties upon exposure to ultrasound energy. In this manner, non-linear body tissues and fluids may release acoustic energy at one or more harmonic frequencies of the fundamental transmit frequency of the ultrasound energy to which they are exposed.

Contrast agents provide another example of a non-linear medium used in some ultrasound imaging applications. Non-linear contrast agents may be introduced into regions of interest in a patient, for example, into the blood stream or body tissues, to highlight these regions from surrounding tissue in the ultrasound image. These agents generally have stronger non-linear properties than the surrounding tissues. Typically, contrast agents have a fundamental resonant frequency and radiate ultrasound energy at a particular harmonic frequency when exposed to high intensity ultrasound energy at the fundamental resonant frequency. An ultrasound imaging system may therefore identify and isolate regions containing a contrast agent by differentiating the ultrasound energy at the particular harmonic frequency associated with the contrast agent from harmonic ultrasound energy associated with the surrounding tissue.

Ultrasound imaging applications utilizing harmonic reflections from either body tissues and/or contrast agents may be limited, however, by the harmonic content of ultrasound energy transmitted to a region of interest. In particular, ultrasound transmit waveforms having a significant harmonic content may result in ultrasound images having undesired artifacts, as well as ultrasound images having reduced contrast between a contrast agent and surrounding tissues. Such artifacts or reduced contrast may be due to undesired high frequency components of the transmit waveform that interfere with desired harmonic reflections from the region of interest.

For example, to reach a region of interest for which an image may be desired, ultrasound energy must often pass through body structures and tissues, such as a chest wall, which include inhomogeneous materials that may significantly distort the waveform profile of ultrasound energy.

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This distortion from inhomogenous materials often results in unwanted artifacts in the resulting image. Since ultrasound waveform distortion from inhomogeneous materials is typically less at lower frequencies, it is advantageous to transmit ultrasound energy at a low fundamental frequency. However, lower frequency ultrasound energy generally results in lower resolution images.

To avoid a loss of resolution associated with lower frequencies, an ultrasound imaging system may detect harmonics reflected from any non-linear tissues being imaged, as discussed above. However, if the ultrasound transmit waveform itself includes a significant harmonic content, higher frequency components of the transmit waveform may not be discernible from the desired harmonic reflections. Moreover, distortion of the higher frequency components of the transmit waveform from inhomogeneous materials, notwithstanding the lower fundamental frequency, may contribute to unwanted artifacts in the resulting image.

In view of the foregoing, it is desirable to transmit ultrasound energy as a waveform having a fundamental frequency, wherein the waveform is substantially free of higher frequency harmonic components of the fundamental frequency, or has low harmonic content. Since higher frequencies experience greater distortion in inhomogeneous materials, as discussed above, reducing higher frequency components in an ultrasound transmit waveform in turn reduces distortion of the ultrasound energy as it passes through body structures and tissues that include inhomogeneous materials. By utilizing ultrasound transmit waveforms having low harmonic content, it is possible for ultrasound imaging systems to obtain clearer images having fewer artifacts from distortion. Additionally, ultrasound imaging applications utilizing low harmonic content ultrasound transmit waveforms and contrast agents benefit from a higher contrast ratio between the contrast agent and surrounding tissue.

In one known technique for reducing the harmonic content of an ultrasound transmit waveform, an electronic pulse generator supplies a burst of pulses having a fundamental frequency to a low pass filter. The duration of the pulses and the number of pulses in the burst are controllable and determine the resulting frequency spectrum of the burst. Such a burst of pulses has a primarily rectangular shape and has a frequency spectrum that includes a number of sidelobes having significant harmonic content. The low pass filter is typically designed as a Gaussian, Bessel or Chebyshev filter to substantially eliminate energy at a particular harmonic frequency from the burst of pulses. The filtered burst of pulses is then applied to ultrasound transducer elements which transmit ultrasound energy having a waveform similar to that of the filtered burst of pulses.

Other proposed techniques for reducing the harmonic content of ultrasound transmit waveforms include using digital signal processing methods and apparatus, such as digital programmable waveform generators, to produce particularly shaped electronic waveforms having low harmonic content, which are then applied to ultrasound transducer elements. Such techniques typically involve synthesizing an electronic signal having a particularly shaped amplitude envelope which includes several cycles of a fundamental or "carrier" frequency. A variety of such electronic signals having frequency spectra that exhibit "sidelobe suppression," or low harmonic content, may be custom synthesized using digital signal processing methods and apparatus.

In one such technique described in Hossack, et al., U.S. Pat. No. 5,740,128, a desired frequency spectrum for an

ultrasound transmit waveform is designed on a computer, and an inverse fast Fourier transform is performed to synthesize a corresponding time domain waveform. The synthesized waveform may be specifically designed to suppress ultrasound energy in a wide band around a particular harmonic frequency. A digital representation of the synthesized waveform is stored in memory, and is applied to a digital-to-analog converter which provides an analog electronic signal of the stored waveform. This analog signal may optionally be passed through a low pass analog filter, such as a Gaussian, Bessel filter or a Chebyshev filter, to further reduce any undesirable high frequency components of the analog signal. This low harmonic content electronic signal is then applied to ultrasound transducer elements to provide ultrasound energy having low harmonic content.

One consequence of the techniques described above is that a significant amount of space is required for the electronic circuitry, for example, the analog filters or any digital signal processing electronics, such as a computer or programmable waveform generator, memory, and digital-to-analog converters, which provide the low harmonic content electronic signal applied to the ultrasound transducer elements. Accordingly, a method and apparatus for transmitting ultrasound energy having low harmonic content is desirable that uses fewer electronic components and requires less space than other proposed techniques.

SUMMARY OF THE INVENTION

The present invention is directed to methods and apparatus for transmitting ultrasound energy having low harmonic content and for receiving harmonic reflections. The methods and apparatus of the invention are simplified with respect to previous solutions for reducing harmonic content in ultrasound transmit waveforms, as discussed above. According to one aspect of the invention, the capacitance of an ultrasound transducer element, as well as any interconnection capacitance associated with one or more signal conductors attached to the transducer element, is utilized as part of a filter that conditions one or more electronic drive signals to provide an ultrasound transmit waveform having low harmonic content. An electronic drive signal input to the filter to drive the ultrasound transducer element may itself have an appreciable harmonic content. This is in contrast to prior art techniques for reducing ultrasound transmit waveform harmonic content, which use pre-filtered and/or synthesized low harmonic content electronic signals to drive an ultrasound transducer element. Additionally, in one aspect, an apparatus according to the invention may be fabricated as a monolithic integrated circuit. In this manner, the methods and apparatus of the invention facilitate the generation of ultrasound energy having low harmonic content and detection of harmonic reflections by using fewer components and circuitry and requiring less space than previous solutions.

In one embodiment, an apparatus according to the invention includes an ultrasound transducer element to output ultrasound energy having an ultrasound transmit waveform with a low harmonic content, wherein the ultrasound transducer element has a capacitance. The apparatus further includes a transducer driver to charge and discharge the ultrasound transducer element based on at least one drive signal input to the transducer driver, wherein the at least one drive signal has a fundamental frequency. The transducer driver charges and discharges the ultrasound transducer element such that the ultrasound transmit waveform has a rise time based on the capacitance and one of an output impedance of the transducer driver and a drive current output by the transducer driver, the one of the output

impedance and the drive current being selected such that the rise time is greater than one-fifth of a period given by a reciprocal of the fundamental frequency.

In one aspect, the fundamental frequency of the drive signal is less than 3.5 MHZ.

In another aspect, the apparatus further includes receive circuitry to detect a reflected ultrasound waveform at a harmonic frequency of the fundamental frequency.

In another aspect, the drive signal has a drive signal harmonic content, and the low harmonic content is substantially less than the drive signal harmonic content.

In another aspect, the apparatus further includes at least one signal conductor electrically connected to the ultrasound transducer element and the transducer driver, wherein the at least one signal conductor has an interconnection capacitance. The interconnection capacitance and the capacitance of the ultrasound transducer element form a combined capacitance, and the rise time is based on the combined capacitance and the one of the output impedance and the drive current.

In another aspect, the transducer driver comprises a controllable voltage source having the output impedance, the controllable voltage source and the ultrasound transducer element form a filter having a cutoff frequency based on the combined capacitance and the output impedance, and the output impedance is selected such that the cutoff frequency is less than a predetermined harmonic frequency of the fundamental frequency.

In another aspect, the predetermined harmonic frequency is the second harmonic frequency.

In another aspect, the transducer driver comprises a controllable switched current source including at least one of a charge circuit and a discharge circuit to output the drive current to the ultrasound transducer element based on the drive signal, and the drive signal includes digital pulse control signals to control at least one of the charge circuit and the discharge circuit.

In another aspect, the digital pulse control signals control the controllable switched current source such that at least one of the charge circuit and the discharge circuit outputs at least two different current values for the drive current.

In another aspect, the charge circuit comprises a plurality of first current sources having a first common terminal controlled by a charge control input, at least one of the first current sources having a second terminal controlled by a first auxiliary control input. The discharge circuit comprises a plurality of second current sources having a first common terminal controlled by a discharge control input, at least one of the second current sources having a second terminal controlled by a second auxiliary control input. The digital pulse control signals are applied to the charge control input, the discharge control input, the first auxiliary control input, and the second auxiliary control input in a predetermined manner to control the plurality of first controllable current sources and the plurality of second controllable current sources to output the drive current.

In another aspect, the ultrasound transmit waveform is a substantially triangular waveform.

In another aspect, the ultrasound transmit waveform comprises at least a first slope and a second slope, the first and second slopes being based on the combined capacitance and the drive current, the first slope having a different magnitude than the second slope.

In another aspect, the ultrasound transmit waveform comprises at least two unique maxima.

In another aspect, the apparatus is fabricated as a monolithic integrated circuit.

In another embodiment, an apparatus according to the invention comprises a plurality of ultrasound transducer elements, each transducer element having a transducer impedance based on a capacitance of the transducer element, and a corresponding plurality of programmable-delay switched current sources to charge and discharge the plurality of ultrasound transducer elements in a selectable manner, each programmable-delay current source outputting a drive current to charge and discharge a respective ultrasound transducer element so as to transmit ultrasound energy having an ultrasound transmit waveform based on the drive current and the transducer impedance, wherein the ultrasound transmit waveform has a low harmonic content. The apparatus further comprises a transducer controller to output common control signals to the plurality of programmable-delay current sources, wherein the ultrasound transmit waveform transmitted by each transducer element is based on selectably delayed versions of the common control signals.

In one aspect, each programmable-delay current source comprises a charge circuit to charge the respective transducer element, a discharge circuit to discharge the respective transducer element, and at least one programmable delay circuit to receive the common control signals and delay instruction signals, and to output the selectably delayed versions of the common control signals to the charge circuit and the discharge circuit, based on the delay instruction signals.

In another aspect, the plurality of programmable-delay current sources and the transducer controller are fabricated as a monolithic integrated circuit.

In another embodiment, a method according to the invention for transmitting ultrasound energy having a low harmonic content ultrasound transmit waveform comprises a step of charging and discharging an ultrasound transducer element using one of a drive voltage applied to the ultrasound transducer element through a drive impedance and a drive current, the drive voltage and the drive current each having a fundamental frequency, the ultrasound transducer element having a capacitance. The method further comprises a step of selecting one of the drive impedance and the drive current such that the ultrasound transmit waveform has a rise time greater than one-fifth of a period given by a reciprocal of the fundamental frequency, the rise time being based on the capacitance and the one of the drive impedance and the drive current.

In one aspect of the method according to the invention, the step of charging and discharging comprises a step of charging and discharging the ultrasound transducer element such that the ultrasound transmit waveform is a complex waveform comprising a sequence of three triangular pulses, wherein a first and last triangular pulse of the sequence each has a first slope magnitude and a first maximum, and a middle triangular pulse of the sequence, occurring between the first and last triangular pulses, has a second slope magnitude greater than the first slope magnitude and a second maximum greater than the first maximum.

In another aspect of the method according to the invention, the step of charging and discharging comprises a step of applying digital pulse control signals having a pulse width to a switched current source to output the drive current, such that the ultrasound transmit waveform has a slope based on the capacitance and the drive current, and the rise time is comparable to the pulse width.

In another aspect, a first magnitude of the low harmonic content of the ultrasound transmit waveform is at least 20 decibels below a second magnitude of a drive current harmonic content of the drive current in a frequency band around a second harmonic frequency of the fundamental frequency.

Other advantages, novel features, and objects of the invention will become apparent from the following detailed description of the invention when considered in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated herein by reference, are not intended to be drawn to scale. In the drawings, each identical or nearly identical component that is illustrated in various figures is represented by a like numeral. For purposes of clarity, not every component may be labeled in every drawing, wherein:

FIG. 1 is a diagram illustrating a portion of an ultrasound imaging system which includes an apparatus according to one embodiment of the invention;

FIG. 2A is a diagram illustrating an apparatus according to one embodiment of the invention;

FIG. 2B is a diagram illustrating an apparatus according to another embodiment of the invention;

FIGS. 3A, 3B, 4A, and 4B are plots showing examples of known ultrasound transmit waveforms and the corresponding frequency spectra;

FIGS. 5A, 5B, 6A, and 6B are plots showing examples of ultrasound transmit waveforms according to one embodiment of the invention and the corresponding frequency spectra;

FIGS. 7 and 8 are circuit diagrams illustrating simple examples of the charge circuit shown in FIG. 2B;

FIG. 9 is a diagram of an example of the apparatus of FIG. 2B according to one embodiment of the invention;

FIG. 10 is a graph illustrating a timing relationship between control signals applied to the apparatus of FIG. 9, according to one embodiment of the invention, and an ultrasound transmit waveform output by the apparatus;

FIG. 11 is a detailed circuit diagram showing an example of the apparatus of FIG. 9 using bipolar junction transistors according to one embodiment of the invention;

FIG. 12 is a detailed circuit diagram showing an example of the apparatus of FIG. 9 using FETs according to one embodiment of the invention;

FIG. 13 is a block diagram of an apparatus for controlling a number of ultrasound transducer elements to transmit ultrasound energy having a low harmonic content according to one embodiment of the invention;

FIG. 14 is a block diagram of a programmable delay current source of the apparatus of FIG. 13; and

FIG. 15 is a detailed block diagram of a portion of the apparatus of FIG. 13.

DETAILED DESCRIPTION

FIG. 1 shows a portion of an ultrasound imaging system for medical applications which includes an apparatus according to one embodiment of the invention. In the system of FIG. 1, one or more arrays 511 of individual ultrasound transducer elements 10 transmit ultrasound energy 517 into a region of interest in a patient 501, and receive reflected ultrasound energy, or echos, from various structures and organs within the patient's body. Transmit circuitry 505

provides electronic signals to the transducer elements 10 of the array 511 to produce the ultrasound energy 517, and receive circuitry 507 processes electronic signals generated by the elements 10 based on the ultrasound energy reflected from the region of interest. The ultrasound energy transmitted by the transducer elements 10 may have a fundamental frequency, and the receive circuitry 507 may detect ultrasound energy reflected from the region of interest at one or more harmonic frequencies of the fundamental frequency.

As illustrated in FIG. 1, the ultrasound imaging system may include a transmit/receive switch 508 to alternately couple, via one or more signal conductors 520, the transmit circuitry 505 and the receive circuitry 507 to the transducer array 511 for respective transmit and receive operations. Alternatively, one group of transducer elements 10 or a transducer array similar to that of array 511, dedicated to transmitting ultrasound energy, may be connected directly to transmit circuitry 505, while another group of transducer elements 10 or another array similar to that of array 511, dedicated to receiving ultrasound energy, may be connected directly to receive circuitry 507. Additionally, transmit circuitry 505, receive circuitry 507, transducer array 511, and transmit/receive switch 509 may be located together in a single package 502, for example a hand-held transducer head which is connected by a flexible cable 516 to an electronics unit (not shown), and may be fabricated as a monolithic integrated circuit. The electronics unit controls the circuitry of the transducer head to form an image of the region of interest in the patient, based on the transmitted and reflected ultrasound energy.

The present invention utilizes the "clamp" capacitance of an ultrasound transducer element 10, as well as any interconnection capacitance between the transducer element and associated circuitry, as part of a "filter" that reduces the harmonic content of a waveform of ultrasound energy 517 transmitted by the transducer element. For example, such a filter may include a portion or all of the transmit circuitry 505, the transducer element 10, and one or more signal conductors 520, and may receive one or more electronic drive signals having a fundamental frequency and a particular frequency spectrum, or harmonic content. An exemplary range of fundamental frequencies of the drive signals suitable for purposes of the invention may given as, but is not limited to, 1 MHz to 10 MHz.

In the filter described above in connection with FIG. 1, the ultrasound transducer element 10 is capacitively charged and discharged through one or more signal conductors 520 by the transmit circuitry 505, based on the drive signals, and converts electrical energy from the drive signals into ultrasound energy 517 such that the ultrasound transmit waveform has low harmonic content. In particular, if the drive signals have an appreciable harmonic content, the ultrasound transmit waveform may have a harmonic content that is substantially less than the harmonic content of the drive signals. Such a low harmonic content ultrasound transmit waveform may be used to expose a region of interest in patient 501 that includes media, such as non-linear tissues and/or contrast agents, which reflect harmonics of the transmit waveform. Receive circuitry 507 may be used to detect such harmonic reflections and generate an ultrasound image of the region of interest having improved contrast and reduced distortion.

A simplified block diagram of an example of an apparatus for transmitting ultrasound energy having low harmonic content, according to one embodiment of the invention, is shown in FIG. 2A. The apparatus of FIG. 2A includes an ultrasound transducer element 10, a transducer driver 20,

and a signal conductor 11 connecting the transducer element 10 and the transducer driver 20. The transducer driver 20 may be included as part of the transmit circuitry 504 of the ultrasound imaging system shown in FIG. 1, and the signal conductor 11 may be, for example, one of the signal conductors 514 shown in FIG. 1. FIG. 2A also shows a capacitance 32 associated with the transducer element 10 and the signal conductor 11. The capacitance 32 represents a combined capacitance based on a "clamp" capacitance of the ultrasound transducer element 10 and any interconnection capacitance associated with the signal conductor 11. For embodiments in which the interconnection capacitance may be negligible, the capacitance 32 represents primarily the capacitance of the ultrasound transducer element 10.

FIG. 2A shows that, in one embodiment of the invention, the transducer driver 20 may include a controllable voltage source 34 having an output impedance 31, shown symbolically in FIG. 2A as resistor R_0. In the apparatus of FIG. 2A, the controllable voltage source 34 charges and discharges the ultrasound transducer element 10 through the output impedance 31 and the signal conductor 11, based on one or more drive signals 40 input to the controllable voltage source 34. Accordingly, in the embodiment of FIG. 2A, the transducer driver 20 functions essentially as a "voltage mode" driver. As discussed above in connection with FIG. 1, the transducer element 10, the signal conductor 11, and the voltage mode transducer driver 20 including the output impedance 31 may be viewed as forming a filter 35 having a cutoff frequency based on the combined capacitance 32 and the output impedance 31.

The cutoff frequency of a filter generally refers to that frequency at which the magnitude of the output of the filter is attenuated by approximately 3 dB (approximately 30%) from some maximum value. For first-order low-pass linear filters such as filter 35, the cutoff frequency in Hz may be expressed in terms of a time constant τ as $1/(2\pi\tau)$, where for the filter 35 τ is given by the product of the output impedance 31 and the combined capacitance 32. An exemplary range of values for the capacitance 32 suitable for purposes of the invention includes, but is not limited to, 10 to 200 picofarads. Similarly, an exemplary range of output impedance values for the voltage mode transducer driver 20 suitable for purposes of the invention includes, but is not limited to, 500 ohms or greater.

In the embodiment of FIG. 2A, the value of the output impedance 31 may be selected and implemented during a fabrication process for the voltage mode transducer driver 20. In particular, the output impedance 31 may be selected such that the cutoff frequency of the filter 35 is less than a predetermined harmonic frequency of a fundamental frequency of one or more drive signals 40. For example, the output impedance 31 may be selected such that the cutoff frequency of filter 35 is less than a second harmonic frequency of the fundamental frequency of the drive signals 40. Accordingly, for drive signals 40 having an appreciable harmonic content, the harmonic content of the ultrasound transmit waveform 44 may be substantially less than the harmonic content of the drive signal.

Alternatively, the drive signal conditioning provided by the apparatus of FIG. 2A may be described in terms of a rise time of the ultrasound transmit waveform 44 output from the filter 35. The rise time of a waveform is commonly defined as the time in which the waveform changes from 10% to 90% of a span between a minimum and maximum value. In the apparatus of FIG. 2A, the ultrasound transmit waveform 44 has a rise time based on the combined transducer/signal conductor capacitance 32 and the output impedance 31 of

the transducer driver **20**. In a preferred embodiment, the rise time is greater than one-fifth of a period given by the reciprocal of the fundamental frequency of the drive signals **40**.

A simplified block diagram of an example of an apparatus for transmitting ultrasound energy having low harmonic content, according to another embodiment of the invention, is shown in FIG. **2B**. In the apparatus of FIG. **2B**, unlike the apparatus of FIG. **2A**, the transducer driver **20** functions essentially as a "current mode" driver. For example, the transducer driver **20** of FIG. **2B** may be a controllable switched current source having a high output impedance which approximates that of an ideal current source having a theoretically infinite output impedance. Similarly to the voltage mode transducer driver of FIG. **2A**, the controllable switched current source transducer driver **20** of FIG. **2B** may be included as part of the transmit circuitry **504** of the ultrasound imaging system shown in FIG. **1**.

In FIG. **2B**, the controllable switched current source transducer driver **20** is shown coupled between a supply voltage V_H, typically in a range of 10 to 200 volts, and ground. FIG. **2B** also shows that the controllable switched current source **20** may include a charge circuit **12** to provide a charge current **26** (I_c) to the ultrasound transducer element **10** and a discharge circuit **16** to conduct a discharge current **28** (I_D) from the ultrasound transducer element **10**. The charge circuit **12** may have a charge control input **14** and the discharge circuit **16** may have a discharge control input **18**.

The charge circuit **12** and the discharge circuit **16** of FIG. **2B** are electrically coupled to provide a drive current **30** (I_T) to the ultrasound transducer element **10**. The drive current **30** is the sum of the charge current **26** and the discharge current **28** as a function of time. The charge control input **14** and the discharge control input **18** may receive one or more electronic drive signals **40** that determine the magnitudes of the charge current **26** and the discharge current **28** as a function of time and hence, determine the drive current **30**.

FIG. **2B** shows that the electronic drive signals received on control inputs **14** and **18** may be digital pulse control signals **40** having a pulse width **42**. An exemplary range of digital control signal pulse widths suitable for purposes of the invention includes, but is not limited to, 50–200 nanoseconds. According to the embodiment of FIG. **2B**, the digital pulse control signals **40** may control at least one of the charge circuit **12** and the discharge circuit **16** to output the drive current **30** such that the ultrasound transmit waveform **44** has a slope **45** based on the combined transducer/signal conductor capacitance **32** and the drive current **30**. In this embodiment, the ultrasound transmit waveform **44** may have a rise time **46** comparable to the pulse width **42**; namely, the rise time **46** and the pulse width **42** may have approximately the same order of magnitude.

In the apparatus of FIG. **2B**, typically the amplitude of the digital pulse control signals **40** determines the magnitudes of the charge current **26** and the discharge current **28**, and the pulse width **42** determines the duration of the charge current **26** and the discharge current **28**. Additionally, the digital pulse control signals **40** are generally applied to control inputs **14** and **18** at different times in a predetermined manner and hence, only one of charge circuit **12** and discharge circuit **16** are operated at any given time. In this manner, the switched current source transducer driver **20** and the ultrasound transducer element **10** of FIG. **2B** function together as a time-dependent filter **36**.

As discussed above in connection with FIG. **2A**, in a preferred embodiment the rise time of the ultrasound trans-

mit waveform **44** is greater than one-fifth of a period given by the reciprocal of the fundamental frequency of the drive signals **40**. Specifically, in the apparatus of FIG. **2B**, the amplitude of the digital pulse control signals **40** may be selected and the control signals **40** may be applied to control inputs **14** and **18** in a predetermined manner such that the rise time **46** of the ultrasound transmit waveform **44** is greater than one-fifth of the pulse width **42**.

In summary, each of the apparatus according to different embodiments of the invention shown in FIGS. **2A** and **2B** receives one or more electronic drive signals and conditions the drive signals to provide an ultrasound transmit waveform having low harmonic content by utilizing the capacitance of both an ultrasound transducer element and one or more signal conductors attached to the ultrasound transducer element as part of a filter. The apparatus according to the embodiment shown in FIG. **2A** includes a "voltage mode" transducer driver, and the ultimate shape of the ultrasound transmit waveform is based on the combined transducer/signal conductor capacitance and an output impedance of the voltage mode transducer driver. The apparatus according to the embodiment shown in FIG. **2B** includes a "current mode" transducer driver, and the ultimate shape of the ultrasound transmit waveform is based on the combined transducer/signal conductor capacitance and a drive current that charges and discharges the ultrasound transducer element.

It is noteworthy that, while prior art transducer drivers are typically designed to have low impedance outputs so as to avoid any deleterious effects on the ultrasound transmit waveform due to the inherent capacitance of the transducer element, the present invention advantageously utilizes the inherent transducer element capacitance and signal conductor capacitance, in combination with either a selected driver output impedance or a drive current provided by a current source having a high output impedance which approximates a theoretically infinite impedance, to provide low harmonic content ultrasound energy.

In both of the apparatus shown in FIGS. **2A** and **2B**, an electrical waveform is produced across the ultrasound transducer element **10** as a result of the charging and discharging of the transducer element due to either an applied voltage or current. The electrical energy of the electrical waveform is converted by the transducer element to ultrasound energy having an ultrasound transmit waveform **44** similar to that of the electrical waveform. In practice, the waveform **44** of ultrasound energy actually transmitted by the transducer element may not be exactly identical to the electrical waveform produced across the ultrasound transducer element and may have a slightly more "softened" or sinusoidal shape close to a waveform peak than that of the electrical waveform. This effect is primarily due to physical limitations of the transducer element, which mechanically vibrates in response to the electrical waveform to produced the ultrasound energy. Accordingly, such a waveform-softening effect may be more pronounced for electrical waveforms having sharp peaks, such as triangular waveforms. For purposes of the present discussion, however, the waveform-softening effect due to physical limitations of the transducer element is assumed to be negligible, and the harmonic content of the electrical waveform produced across the ultrasound transducer element **10** and the ultrasound transmit waveform **44** itself are assumed to be substantially similar.

The concept of harmonic content of waveforms in general will now be discussed briefly with reference to FIGS. **3A–6C**. FIGS. **3A** and **3B** through **6A** and **6B** are graphs

which illustrate four examples of waveforms and their corresponding frequency spectra. For each of FIGS. 3A, 4A, 5A, and 6A, the horizontal axis of the graphs represents time in microseconds (μS), and the vertical axis represents waveform amplitude in arbitrary units. For each of FIGS. 3B, 4B, 5B, and 6B, the horizontal axis of the graph represents frequency in megahertz (MHz), and the vertical axis represents the relative strength of a particular frequency component of the waveform, or spectrum, in units of decibels (dB). While, for purposes of comparison, FIGS. 3A and 4A illustrate waveforms that are employed in known ultrasound imaging systems, FIGS. 5A and 6A show examples of ultrasound transmit waveforms according to the present invention, having an appreciably lower harmonic content than the waveforms of FIGS. 3A and 4A.

FIG. 3A shows a single square pulse waveform **50** having a pulse width **49** of approximately 0.5 microseconds. The pulse width **49** is chosen for purposes of illustration only, and is not intended to be limiting. According to fundamental principles of Fourier transformation of waveforms between the time domain and the frequency domain, the fundamental frequency of such a square pulse waveform **50** is approximately equal to the reciprocal of the pulse width **49**. Accordingly, the square pulse waveform **50** has a fundamental frequency of approximately 1/0.5 microseconds, or 2 MHz.

FIG. 3B shows a spectrum **51** in the frequency domain corresponding to the single square pulse waveform **50**. The spectrum **51** illustrates the relative strengths of the various frequency components present in the single square pulse waveform **50**. A portion or "band" of the spectrum **51** that includes the fundamental frequency of 2 MHz is indicated along the horizontal frequency axis of FIG. 3B by reference character **600**. Similarly, a band of the spectrum **51** including the second harmonic of the fundamental frequency, namely, a frequency component at 4 MHz, is indicated along the horizontal frequency axis of FIG. 3B by reference character **602**. In each of FIGS. 3B, 4B, 5B, and 6B, the widths of the bands **600** and **602** are chosen for purposes of illustration to be equal to the fundamental frequency of the example waveforms, namely 2 MHz.

The spectrum **51** of FIG. 3B comprises a plurality of sidelobes **58**. In general, for Fourier transformation of waveforms from the time domain to the frequency domain, the relative strength of the sidelobes **58** decreases as the frequency difference from the fundamental frequency increases. Accordingly, the harmonic content, contained within the sidelobes **58** of a waveform, generally decreases with increasing frequency from the fundamental. More specifically, each waveform profile in time corresponds to a frequency spectrum having a particular distribution of sidelobes **58** with varying relative strengths. Hence, the harmonic content of a waveform is directly related to the shape or profile of the waveform as a function of time. As a result, a waveform profile may be chosen to achieve an appreciable reduction of harmonic content, or "sidelobe suppression," across the entire frequency spectrum, in one or more frequency bands of interest, or at or near a particular frequency of interest.

Using 0.0 dB as a reference for the spectra of FIGS. 3B, 4B, 5B, and 6B at the fundamental frequency of 2 MHz, FIG. 3B shows that the square pulse waveform **50** has a spectrum **51** with significant frequency components in the band **600** around the fundamental frequency of 2 MHz. However, spectrum **51** indicates that the harmonic content of square pulse waveform **50** is attenuated very near the second harmonic frequency of 4 MHz, and shows an absence of

appreciable second harmonic content at 4 MHz. However, spectrum **51** nonetheless shows a significant harmonic content in the band **602** around the second harmonic frequency, and in particular, a harmonic content of approximately −10 dB near the frequencies 3.3 and 5 MHz.

FIG. 4A shows a plot of waveform **52** which includes two square pulses, each pulse having a pulse width **49** of approximately 0.5 microseconds. FIG. 4B shows the corresponding spectrum **53** for the waveform **52**. As in FIG. 3B, a band of the spectrum **53** which includes the fundamental frequency 2 MHz is indicated by reference character **600**, and a band of the spectrum **53** including the second harmonic frequency 4 MHz is indicated by reference character **602**. As compared to the spectrum **51** of FIG. 3B, the spectrum **53** of FIG. 4B includes an increased number of sidelobes **58**. Furthermore, the relative harmonic content of spectrum **53** in band **602** is notably decreased compared with that of the band **602** of spectrum **51**. In particular, while the harmonic content of spectrum **51** in band **602** is as high as −10 dB or greater, the band **602** of spectrum **53** in FIG. 4B has a harmonic content of only up to approximately −15 dB or less, or a sidelobe suppression of approximately 15 dB or greater. Hence, the two-square-pulse waveform **52** has a low harmonic content around the second harmonic frequency compared with that of the single-square-pulse waveform **50**.

FIGS. 5 and 6 show time domain and frequency domain illustrations, similar to the plots of FIGS. 3 and 4, for two exemplary ultrasound transmit waveforms according to the invention having triangular shapes. FIG. 5A shows a waveform **54** including two triangle pulses, each pulse having a rise time **59** of approximately 0.5 microseconds. FIG. 5B shows the spectrum **55** corresponding to the waveform **54**. The harmonic content of the spectrum **55** in the band **602** around the second harmonic frequency has a maximum relative strength of between −25 and −30 dB, or a sidelobe suppression of between 25 and 30 dB.

FIG. 6A shows a complex triangular waveform **56** having at least two unique maxima **80** and **82**, including three triangle pulses, each pulse having a rise time **59** of approximately 0.5 microseconds. FIG. 6B shows a spectrum **57** corresponding to the waveform **56**. The harmonic content of spectrum **57** in the band **602** around the second harmonic frequency has a relative strength of less than −30 dB, or a sidelobe suppression of greater than 30 dB. Hence, of the four example waveforms illustrated in FIGS. 3 through 6, waveform **56** shown in FIG. 6A has the most significantly low harmonic content, or the greatest sidelobe suppression, particularly around the second harmonic frequency.

It should be appreciated that while a particular time scale for the waveforms and corresponding frequency range for the spectra are given in the plots of FIGS. 3 to 6, a variety of waveform profiles according to the invention may be chosen to achieve sidelobe suppression, or low harmonic content in the spectra, over a variety of frequencies and ranges. For example, while predominantly triangular waveforms are illustrated in FIGS. 5A and 6A as low harmonic content waveforms according to the invention, a variety of trapezoidal shaped waveforms may also provide a suitably low harmonic content for purposes of the invention. The time scale, frequency range, and waveform shapes of FIGS. 5–6 are chosen for purposes of illustrating the general concepts of sidelobe suppression and reducing harmonic content of waveforms according to the invention, and are not intended to be limiting.

Returning now to the apparatus shown in FIG. 2B having a current mode transducer driver, the charge circuit **12** and

the discharge circuit **16** of the controllable switched current source transducer driver **20** may each include bipolar junction transistors (BJTS) or field effect transistors (FETs) as high impedance current sources to provide the charge current **26** and conduct the discharge current **28**. FIG. **7** shows an example of the charge circuit **12** including a BJT **22** as a current source according to one embodiment of the invention, providing charge current **26** from the collector of the BJT, while FIG. **8** shows an example of the charge circuit **12** including an FET **24** as a current source according to one embodiment of the invention, providing charge current **26** from the drain of the FET.

The BJT **22** or the FET **24** of FIGS. **7** and **8** may be high voltage devices, capable of withstanding voltages of between 25–100 volts. Additionally, while FIG. **7** shows only one BJT and FIG. **8** shows only one FET for the charge circuit **12**, any number of BJTs or FETs, arranged in a variety of serial and/or parallel configurations, may be used for either the charge circuit **12** or the discharge circuit **16** to provide high impedance current terminations which approximate those of an ideal current source having a theoretically infinite impedance.

FIG. **9** is a diagram of an example of the controllable switched current source transducer driver **20** of the apparatus of FIG. **2B** according to one embodiment of the invention. Unlike the linear filter **35** of FIG. **2A** which employs a voltage mode transducer driver, the switched current source **20** of FIG. **9** essentially functions to "piece together" an electrical waveform across ultrasound transducer element **10**, based on two or more different charge/discharge rates, or "slopes." In this manner, the switched current source **20** of FIG. **9** is particularly useful for generating an electrical waveform, and hence an ultrasound transmit waveform **44**, similar to the triangular waveform **56** shown in FIG. **6A**, which has at least two unique maxima and at least two different slope magnitudes.

In the switched current source **20** of FIG. **9**, the charge circuit **12** includes current sources **200** and **201** having a common terminal **205**, serving as the output of the current sources **200** and **201**. This output is controlled by charge control input **14**, shown symbolically in FIG. **9** as operating (opening and closing) a switch **206**. Current source **200** additionally has a terminal controlled by a first auxiliary control input **70**, shown symbolically in FIG. **9** as operating switch **204**.

Similarly, the discharge circuit **16** of FIG. **9** includes current sources **202** and **203** having a common terminal **209** which is controlled by discharge control input **18**, shown symbolically in FIG. **9** as operating switch **210**. Current source **202** additionally has a terminal controlled by a second auxiliary control input **72**, shown symbolically in FIG. **9** as operating switch **208**. While FIG. **9** shows the first and second auxiliary control inputs **70** and **72** connected together to receive the same control signal, auxiliary control inputs **70** and **72** may be separate and may operate independently, receiving two or more distinct control signals.

The charge circuit **12** and discharge circuit **16** of FIG. **9** are electrically coupled to provide the drive current **30**, and may be operated to output drive current **30** to the ultrasound transducer element **10** such that ultrasound energy having a wide variety of ultrasound transmit waveforms **44** is transmitted from the transducer element **10**. For example, as discussed above in connection with FIG. **2B**, the switched current source **20** of FIG. **9** may be operated by applying digital pulse control signals **40** such that at least one of the

charge circuit **12** and the discharge circuit **16** outputs at least two different current values for the drive current **30**. In particular, the digital pulse control signals **40** may be applied to the charge control input **14**, the discharge control input **18**, and the first and second auxiliary control inputs **70** and **72** in a predetermined manner, such that the drive current **30** produces an ultrasound transmit waveform **44** having at least two distinct slopes and at least two unique maxima, similar to the waveform shown in FIG. **6A**.

FIG. **10** is a timing diagram of the digital pulse control signals applied to the switched current source **20** of FIG. **9** according to one embodiment of the invention, and the resulting electrical waveform generated across the ultrasound transducer element **10** and, hence, essentially the ultrasound transmit waveform **44** transmitted by the transducer element. The horizontal axis **100** of FIG. **10** indicates time t. The lower three plots of FIG. **10** illustrate the digital pulse control signals PULL__UP, PULL__DOWN and BOOST. As shown in FIGS. **9** and **10**, in this embodiment the PULL__UP control signal is applied to the charge control input **14**, the PULL__DOWN signal is applied to the discharge control input **18**, and the BOOST signal is applied to the first and second auxiliary control inputs **70** and **72**.

With reference to FIGS. **9** and **10**, a first pulse **340** of the PULL__UP control signal closes switch **206** so that current source **201** charges ultrasound transducer element **10** during a "charge phase." As shown in FIG. **10**, during pulse **340** the PULL__DOWN and BOOST control signals remain in a logic low state so that switches **204**, **208**, and **210** remain open. The ultrasound transducer element **10** charges for a time indicated by the pulse width **42** of pulse **340**. The resulting ultrasound transmit waveform **44** has a rise time **46** comparable to the pulse width **42**, and a slope **45** based on the capacitance **32** and the drive current **30**, which at this point is provided only by current source **201**. The waveform **44** reaches a first maximum value **80** after the rise time **46**, at the end of pulse **340**.

After pulse **340**, the PULL__UP control signal changes to a logic low state, at which time pulse **342** of the PULL__ DOWN signal is applied to discharge control input **18**. As a result, switch **206** is opened and switch **210** is closed, so that current source **203** conducts current from the ultrasound transducer element **10** during a "discharge phase." In the example of FIG. **10**, pulse **342** has a pulse width **42** similar to that of pulse **340**, so that the slope **45'** of ultrasound transmit waveform **44** during this discharge phase is substantially equal in magnitude but opposite in sign to the slope **45** during the charge phase of the ultrasound transducer element **10**. While FIG. **10** shows similar pulse widths **42** for each of the pulses **340**, **342**, **344**, **348**, **350**, and **352** of the PULL__UP and PULL__DOWN control signal, it should be appreciated that each of the control signal pulses may have a unique pulse width, which in turn determines a respective rise or fall time of a portion of the ultrasound transmit waveform **44**.

Returning to the graph of FIG. **10**, after pulse **342** the PULL__DOWN signal changes to a logic low state as pulse **344** of the PULL-UP signal is applied to charge control input **14**. At this time, pulse **346** of the BOOST signal is applied to first and second auxiliary control input **70** and **72**. While switch **210** is opened, switches **204** and **206** are both closed so that both of current sources **200** and **201** provide drive current **30** to the ultrasound transducer element **10**. While pulse **344** has a pulse width **42** similar to that of pulses **340** and **342** in FIG. **10**, the drive current **30** at this point is nonetheless greater than the drive current provided to, or drawn from, the ultrasound transducer element during the

pulses **340** and **342**, respectively, due to the two current sources **200** and **201** providing the drive current simultaneously. Accordingly, the magnitude of slope **47** of ultrasound transmit waveform **44** is greater than that of slope **45** as a result of the increased drive current, and hence, the magnitude of the ultrasound transmit waveform **44** reaches a higher maximum value **82** after substantially the same rise time **46**.

Continuing with FIG. **10**, while pulse **346** of the BOOST signal is still applied to first and second auxiliary control inputs **70** and **72**, after pulse **344** the PULL__UP control signal subsequently changes to a logic low state and pulse **348** of the PULL_DOWN signal is applied to discharge control input **18**. As a result, switch **206** is opened and switches **208** and **210** are closed, allowing both current sources **202** and **203** to draw current from ultrasound transducer element **10**. During the assertion of pulse **348**, the slope **47**' of ultrasound transmit waveform **44** is substantially equal in magnitude but opposite in sign to the slope **47**.

Following pulse **348**, both of the PULL_DOWN and BOOST signals change to a logic low state, thereby opening switches **210**, **204**, and **208**, while pulse **350** of the PULL__UP signal is applied to the charge control input **14**, again closing switch **206**, and allowing current source **201** to charge the ultrasound transducer element **10**. Since only one current source **201** is charging ultrasound transducer element **10** as this point, the slope **45** of ultrasound transmit waveform **44** during pulse **350** is less than the slope **47** and is similar to the slope of waveform **44** during pulse **340**. Following pulse **350**, the PULL__UP signal changes to a logic low state, and pulse **352** of the PULL_DOWN signal is applied to discharge control input **18**, thereby closing switch **210** and allowing current source **203** to discharge the ultrasound transducer element **10**.

According to the digital pulse control sequence described above in the example of FIG. **10**, a complex triangular ultrasound transmit waveform **44** is generated, having two distinct slope magnitudes **45** and **47** and at least two unique maxima **80** and **82**, similar to the waveform shown in FIG. **6A**. It should be appreciated that, while FIG. **9** shows two switched current sources for each of the charge and discharge circuits of controllable current source **20**, any number of current sources and switches, controlled by any number of control inputs, may be employed in the charge circuit **12** and the discharge circuit **16**, in a number of configurations, to "piece together" a wide variety of low harmonic content waveforms having several distinct slope magnitudes and unique maxima. Additionally, as discussed above, while FIG. **10** shows similar pulse widths for the control signals, a variety of pulse widths and sequences may be used for the control signals, in conjunction with the apparatus of FIG. **9** or similar apparatus employing a different number of current sources and/or differently configured control inputs, to generate a variety of low harmonic content waveforms.

FIGS. **11** and **12** each show a detailed circuit diagram of an example of the apparatus of FIG. **9** employing current mode transducer drivers according to one embodiment of the invention. The example of FIG. **11** uses BJTs and outputs the drive current **30** via collectors of BJTs, while the example of FIG. **12** uses FETs and outputs the drive current **30** via drains of FETs. As discussed above in connection with FIGS. **7** and **8**, the collectors of BJTs and the drains of FETs provide high impedance current terminations which approximate those of an ideal current source having a theoretically infinite impedance.

In the circuit of FIG. **11**, the BOOST control signal and the PULL__UP control signal, as shown in FIG. **10**, are

applied to logic AND gate **604** to provide a gated BOOST signal **75**. Similarly, the BOOST control signal and the PULL_DOWN control signal, as shown in FIG. **10**, are applied to logic AND gate **606** to provide gated BOOST signal **77**. The charge circuit **12** of FIG. **11** includes two level shifters **78** and **79**, two BJT switches **404** and **406**, a first current source **400** comprising resistor R1 and BJT **414**, and a second current source **401** comprising resistor R2 and BJT **414**. The BJT switches **404** and **406** function similarly to the switches **204** and **206** of FIG. **9**, while the current sources **400** and **401** function similarly to the current sources **200** and **201** of FIG. **9**.

In the circuit of FIG. **11**, level shifter **78** is coupled between charge control input **14** and BJT switch **406**, and serves to shift the TTL logic level of the PULL__UP control signal to provide a switching current to the base of BJT switch **406** that is referenced to the supply voltage V_H applied to the emitters of BJT switches **404** and **406**. Similarly, level shifter **79** is coupled to receive the TTL logic level of the gated BOOST signal **75** and to provide a switching current to the base of BJT switch **404** that is referenced to the supply voltage V_H.

When the PULL__UP control signal applied to charge control input **14** is such that BJT switch **406** conducts current, the current source **401** provides charge current **26** from the collector of BJT **414**. The charge current **26** provided by current source **401** is determined by the resistance value of resistor R2, the supply voltage V_H, and a bias voltage BIAS1 applied to the base **74** of BJT **414**. It should be appreciated that a variety of resistor values may be selected for resistor R2 and the supply voltage V_H and the BIAS1 signal may be varied to provide a variety of charge currents **26** depending on a particular application.

In a manner similar to that of current source **401**, current source **400**, which includes resistor R1 and BJT **414**, may be controlled to provide current, in conjunction with current source **401**, to output charge current **26**. When both the PULL__UP control signal and the BOOST control signal are at a logic high level, the gated BOOST signal **75**, via level shifter **79**, causes BJT switch **404** to conduct current, hence activating current source **400**. The charge current **26** is then the combined current contributions from current sources **400** and **401**. As with current source **401**, the current provided by current source **400** is determined by the resistance value of resistor R1, the supply voltage VH, and the BIAS1 signal applied to the base **74** of BJT **414**. For many applications, the values of resistors R1 and R2 may be chosen to be equal.

The discharge circuit **16** of FIG. **11** functions similarly to charge circuit **12**, as described above. In FIG. **11**, discharge circuit **16** includes two BJT switches **408** and **410**, which function similarly to switches **208** and **210**, respectively, of FIG. **9**. The base of BJT switch **408** is coupled to receive the gated BOOST signal **77**, and the base of BJT switch **410** serves as the discharge control input **18** which receives the PULL_DOWN control signal. Current source **402** comprises resistor R3 and BJT **412**, while current source **403** comprises resistor R4 and BJT **412**. Current sources **402** and **403** function similarly to current sources **202** and **203**, respectively, of FIG. **9**. A BIAS2 signal is applied to the base **76** of BJT **412**, and together with the supply voltage V_H and the resistance values of resistors R3 and R4, determines the current drawn by each of the current sources **402** and **403**, respectively. In the circuit of FIG. **11**, the collector of BJT **414** and the collector of BJT **412** of the charge and discharge circuits, respectively, are coupled to provide the drive current **30**. The switched current source **20** of FIG. **11** may be fabricated as a monolithic integrated circuit.

The circuit of FIG. 12 functions similarly to that of FIG. 11, but employs FETs rather than BJTs. In the charge circuit 12 of FIG. 12, FET current mirror 500 and FET 513 essentially function as current source 201 of FIG. 9, while current mirror 500 and FET 512 essentially function as current source 200 of FIG. 9. Reference current source 514, which is applied to the gates of FETs 512 and 513 in the circuit of FIG. 12, determines the magnitude of charge current 26. FET 506 corresponds to switch 206 of FIG. 9, while FET 504 essentially functions as switch 204 of FIG. 9, receiving the PULL__UP control signal and the BOOST control signal on their respective gates. The output 515 of current mirror 500 provides the charge current 26.

In the discharge circuit 16 of FIG. 12, FET 510 functions similarly to switch 210 of FIG. 9, wherein the gate of FET 510 serves as the discharge control input 18 which receives the PULL__DOWN control signal. FET 508 functions similarly to switch 208 of FIG. 9, wherein the gate of FET 508 serves as the second auxiliary control input 72 which receives the BOOST control signal. FET 519 functions similarly to current source 203 of FIG. 9, while FET and 518 functions similarly to current source 202 of FIG. 9. FETs 518 and 519 are biased at their gates by reference current source 514 which, similarly to the charge current 26, determines the magnitude of the discharge current 28. As a result, the magnitude of the reference current 514 determines an appropriate range of values for the charge current 26 and the discharge current 28, and hence, the drive current 30. As in the circuit of FIG. 11, the switched current source 20 of FIG. 12 may be fabricated as a monolithic integrated circuit.

While the foregoing discussion has been directed primarily to an ultrasound transmit waveform generated by a single ultrasound transducer element, the method and apparatus of the invention may be effectively implemented to provide an ultrasound transmit waveform having low harmonic content from a number of ultrasound transducer elements. FIG. 13 is a block diagram of an apparatus for controlling a number of ultrasound transducer elements to transmit ultrasound energy having low harmonic content, according to one embodiment of the invention.

The apparatus of FIG. 13 includes a plurality of ultrasound transducer elements 10, each transducer element having a capacitance 32. While in practice the respective capacitances 32 of the transducer elements 10 may not be precisely equal, substantially similar capacitances are assumed, which is suitable for purposes of the invention. Additionally, as discussed above in connection with FIG. 2A, the capacitance 32 is assumed, for purposes of discussion, to include any interconnection capacitance due to the signal conductors 11. Programmable delay current sources 90 charge and discharge the ultrasound transducer elements 10 via the signal conductors 11 in a selectable manner. Each programmable delay current source 90 charges and discharges a respective ultrasound transducer element 10 so as to transmit ultrasound energy having an ultrasound transmit waveform, shown in FIG. 13 as waveforms 440, 442, 444 and 446 for respective transducer elements 10, wherein the ultrasound transmit waveform has a low harmonic content based on the capacitance 32.

The apparatus of FIG. 13 may further include a transducer controller 60 to output common control signals 300 to the plurality of programmable delay current sources 90. The ultrasound transmit waveforms 440, 442, 444, and 446 transmitted by each transducer element 10 are based on selectably delayed versions of the common control signals 300. The common control signals 300 may be, for example, digital pulse control signals similar to those described above

in connection with FIGS. 9 and 10. One example of a transducer controller 60 suitable for purposes of the invention includes, but is not limited to, a synchronous state machine which receives a clock signal 64 and a trigger signal 62, and generates one or more digital pulses in a predetermined timing sequence as the common control signals 300.

FIG. 14 is a block diagram of an example of one programmable delay current source 90 of the apparatus of FIG. 13. Each programmable delay current source 90 may comprise a switched current source 20 that includes a charge circuit 12 to charge a respective transducer element 10, and a discharge circuit 16 to discharge the respective transducer element. Each current source 90 may additionally include at least one programmable delay circuit 92 to receive the common control signals 300 and delay instruction signals 302 and to output selectively delayed versions 310 and 312 of the common control signals 300 to the charge circuit 12 and the discharge circuit 16, based on the delay instruction signals 302.

With reference again to FIG. 13, each programmable delay current source 90 may receive unique delay instructions signals 302, 304, 306, and 308, so that the respective ultrasound transmit waveforns 440, 442, 444 and 446 output by the ultrasound transducer elements 10 have similar waveform profiles but are delayed with respect to one another in time. By selectively delaying the common control signals 300, the apparatus of FIG. 13 allows a waveform of ultrasound energy transmitted by a plurality of transducer elements to be steered and/or focused to a particular region of interest.

In FIG. 14, the switched current source 20, including charge circuit 12 and discharge circuit 16, may be similar to any one of the circuits discussed in connection with FIGS. 2, 9, 11, or 12. While FIG. 14 shows two selectively delayed versions 310 and 312 of the common control signals 300 coupled to the charge circuit 12 and the discharge circuit 16, respectively, any number of selectively delayed control signals may be provided by the programmable delay circuit 92 and applied to either one or both of the charge circuit 12 and the discharge circuit 16 to operate the controllable current source 20. Additionally, with reference again to FIG. 13, the programmable delay current sources 90 and the transducer controller 60 may be fabricated as a monolithic integrated circuit.

FIG. 15 is a more detailed block diagram of a portion of the circuit of FIG. 13, constructed and arranged to provide ultrasound transmit waveforms from a plurality of transducer elements in a manner similar to that described in connection with FIGS. 9 and 10 for a single ultrasound transducer element. More specifically, the apparatus of FIG. 15 may be utilized to provide a complex triangular ultrasound transmit waveform having at least two distinct slope magnitudes and at least two unique maxima from a plurality of transducer elements.

In FIG. 15, common control signals 300 include signals 320, 322, and 324, output from transducer controller 60. Each signal 320, 322, and 324 is applied to a respective programmable delay 94 in the programmable delay circuit 92 of current source 90 (FIG. 13) for each ultrasound transducer element. Each programmable delay circuit 92 receives delay instruction signals as described above in connection with FIGS. 13 and 14, shown in FIG. 15 as signals 302 and 304, and outputs selectively delayed versions of the common control signals 320, 322, and 324 based on the delay instruction signals. While FIG. 15 shows only

two programmable delay circuits **92** receiving delay instruction signals **302** and **304**, respectively, any number of programmable delay circuits **92** may be utilized, as determined by the number of ultrasound transducer elements employed in the ultrasound imaging system. Furthermore, the delay instruction signals for each programmable delay circuit **92** may or may not be unique, and depends on the manner in which ultrasound energy is to be directed by the transducer elements.

In FIG. **15**, the selectively delayed versions of the common control signals **300** output by the programmable delay circuits **92** correspond to the BOOST, PULL__UP and PULL__DOWN signals shown in FIGS. **9** and **10**. In the apparatus of FIG. **15**, the outputs of programmable delay circuits **92** are labeled, for purposes of illustration, with reference characters **14, 18, 70,** and **72,** and **14', 18', 70',** and **72',** respectively, to correspond to the charge control input, the discharge control input, and the first and second auxiliary control inputs of the circuit of FIG. **9** for two of the ultrasound transducer elements shown in FIG. **13**. In practice, the apparatus of FIG. **15** may generate a selectively delayed version of the BOOST, PULL__UP and PULL__ DOWN control signals for each ultrasound transducer element of an imaging system so that a waveform of ultrasound energy having low harmonic content may be directed by the ultrasound transducer elements into a region of interest.

Having thus described at least one illustrative embodiment of the invention, various alterations, modifications and improvements will readily occur to those skilled in the art. Such alterations, modifications and improvements are intended to be within the spirit and scope of the invention. Accordingly, the foregoing description is by way of example only and is not intended as limiting.

What is claimed is:

1. Apparatus comprising:

an ultrasound transducer element to output ultrasound energy having an ultrasound transmit waveform with a low harmonic content, the ultrasound transducer element having a capacitance; and

an analog transducer driver to charge and discharge the ultrasound transducer element based on at least one drive signal input to the analog transducer driver, the at least one drive signal having a fundamental frequency,

wherein the analog transducer driver charges and discharges the ultrasound transducer element such that the ultrasound transmit waveform has a rise time based on the capacitance and one of an output impedance of the analog transducer driver and a drive current output by the analog transducer driver, the one of the output impedance and the drive current being selected such that the rise time is greater than one-fifth of a period given by a reciprocal of the fundamental frequency.

2. The apparatus of claim **1**, wherein the fundamental frequency is less than 3.5 MHz.

3. The apparatus of claim **1**, further including receive circuitry to detect a reflected ultrasound waveform at a harmonic frequency of the fundamental frequency.

4. The apparatus of claim **1**, wherein:

the drive signal has a drive signal harmonic content; and

the low harmonic content is substantially less than the drive signal harmonic content.

5. The apparatus of claim **1**, further including at least one signal conductor electrically connected to the ultrasound transducer element and the analog transducer driver, wherein:

the at least one signal conductor has an interconnection capacitance;

the interconnection capacitance and the capacitance of the ultrasound transducer element form a combined capacitance; and

the rise time is based on the combined capacitance and the one of the output impedance and the drive current.

6. The apparatus of claim **5**, wherein:

the analog transducer driver comprises a controllable voltage source having the output impedance;

the controllable voltage source and the ultrasound transducer element form a filter having a cutoff frequency based on the combined capacitance and the output impedance; and

the output impedance is selected such that the cutoff frequency is less than a predetermined harmonic frequency of the fundamental frequency.

7. The apparatus of claim **6**, wherein the predetermined harmonic frequency is the second harmonic frequency.

8. The apparatus of claim **5**, wherein:

the analog transducer driver comprises a controllable switched current source including at least one of a charge circuit and a discharge circuit to output the drive current to the ultrasound transducer element based on the drive signal; and

the drive signal includes digital pulse control signals to control at least one of the charge circuit and the discharge circuit.

9. The apparatus of claim **8**, wherein the ultrasound transmit waveform is a substantially triangular waveform.

10. The apparatus of claim **8**, wherein the charge circuit and the discharge circuit each include a high-voltage bipolar junction transistor.

11. The apparatus of claim **8**, wherein the charge circuit and the discharge circuit each include a high-voltage FET.

12. The apparatus of claim **8**, wherein the digital pulse control signals control the controllable switched current source such that at least one of the charge circuit and the discharge circuit outputs at least two different current values for the drive current.

13. The apparatus of claim **12**, wherein:

the charge circuit comprises a plurality of first current sources having a first common terminal controlled by a charge control input, at least one of the first current sources having a second terminal controlled by a first auxiliary control input;

the discharge circuit comprises a plurality of second current sources having a first common terminal controlled by a discharge control input, at least one of the second current sources having a second terminal controlled by a second auxiliary control input; and

the digital pulse control signals are applied to the charge control input, the discharge control input, the first auxiliary control input, and the second auxiliary control input in a predetermined manner to control the plurality of first controllable current sources and the plurality of second controllable current sources to output the drive current.

14. The apparatus of claim **13**, wherein the ultrasound transmit waveform comprises at least a first slope and a second slope, the first and second slopes being based on the combined capacitance and the drive current, the first slope having a different magnitude than the second slope.

15. The apparatus of claim **14**, wherein the ultrasound transmit waveform comprises at least two unique maxima.

16. The apparatus of claim **13**, wherein the controllable current source is fabricated as a monolithic integrated circuit.

17. Apparatus comprising:

a plurality of ultrasound transducer elements, each transducer element having a transducer impedance based on a capacitance of the transducer element;

a corresponding plurality of programmable-delay switched analog current sources to charge and discharge the plurality of ultrasound transducer elements in a selectable manner, each programmable-delay current source outputting a drive current to charge and discharge a respective ultrasound transducer element so as to transmit ultrasound energy having an ultrasound transmit waveform based on the drive current and the transducer impedance, wherein the ultrasound transmit waveform has a low harmonic content; and

a transducer controller to output common control signals to the plurality of programmable-delay current sources, the ultrasound transmit waveform transmitted by each transducer element being based on selectably delayed versions of the common control signals.

18. The apparatus of claim 17, wherein the ultrasound transmit waveform is a substantially triangular waveform.

19. The apparatus of claim 17, wherein each programmable-delay current source comprises:

a charge circuit to charge the respective transducer element;

a discharge circuit to discharge the respective transducer element; and

at least one programmable delay circuit to receive the common control signals and delay instruction signals, and to output the selectably delayed versions of the common control signals to the charge circuit and the discharge circuit, based on the delay instruction signals.

20. The apparatus of claim 17, wherein the plurality of programmable-delay current sources and the transducer controller are fabricated as a monolithic integrated circuit.

21. A method for transmitting ultrasound energy having a low harmonic content ultrasound transmit waveform, comprising steps of:

using an analog drive circuit, charging and discharging an ultrasound transducer element using one of a drive voltage applied to the ultrasound transducer element through a drive impedance and a drive current, the drive voltage and the drive current each having a fundamental frequency, the ultrasound transducer element having a capacitance; and

selecting one of the drive impedance and the drive current such that the ultrasound transmit waveform has a rise time greater than one-fifth of a period given by a reciprocal of the fundamental frequency, the rise time being based on the capacitance and the one of the drive impedance and the drive current.

22. The method of claim 21, wherein the step of charging and discharging comprises a step of charging and discharging the ultrasound transducer element such that the ultrasound transmit waveform is a complex waveform comprising a sequence of three triangular pulses, wherein:

a first and last triangular pulse of the sequence each has a first slope magnitude and a first maximum; and

a middle triangular pulse of the sequence, occurring between the first and last triangular pulses, has a second slope magnitude greater than the first slope magnitude and a second maximum greater than the first maximum.

23. The method of claim 21, wherein:

the step of charging and discharging comprises a step of applying digital pulse control signals having a pulse width to a switched current source to output the drive current, such that the ultrasound transmit waveform has a slope based on the capacitance and the drive current, and the rise time is comparable to the pulse width.

24. The method of claim 23, wherein a first magnitude of the low harmonic content of the ultrasound transmit waveform is at least 20 decibels below a second magnitude of a drive current harmonic content of the drive current in a frequency band around a second harmonic frequency of the fundamental frequency.

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